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On the eclogites of Norway.

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ON THE ECLOGITES OF NORWAY

BY

PENTTI ESKOLA

WITH 14 FIGURES IN THE TEXT AND 3 PLATES

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A. W. BRØGGERS BOKTRYKKERI A/S

PREFACE.

The present paper is a result of work done in the Mineralogical Institute of the University of Christiania in 1920. Professor V. M. Goldschmidt, Director of the Institute, kindly allowed me the free use of all its resources, and let his assistant, Mr. L. Thomassen, execute for me a number of chemical analyses and help me in my own analytical work. Professor J. Schetelig, Director of the Mineralogical and Geological Museum of the University of Christiania, with great courtesy placed the collections of Norwegian eclogites and related rocks at my disposal, and let his preparator, Mr. A. Granli, make thin sections of the rocks. Dr. H. H. Reusch, Director of the Geological Survey of Norway, let me use his unpublished notes on certain parts of the eclogite-bearing regions in Western Norway. Professor Dr. C. F. Kolderup, Director of Bergens Museum, gave me specimens of eclogites from the Bergen region for study. Finally the Directors of the Mineralogical Institute and the Museums of Christiania and Bergen promoted my work in the most valuable way by giving me an opportunity to make excursions in some of the most interesting eclogite-bearing regions in the districts of Nordfjord and Søndmøre in Western Norway, at the expense of these institutions.

For all their amiable helpfulness shown to me I wish to express to these gentlemen my most sincere thanks. I also have to thank numerous other Norwegian geologists and other persons who all showed to me, an alien in their country, the kindest friendliness.

I am also very much obliged to Dr. H. S. Washington and Mr. O. Andersen for their kindness in making grammatical corrections in my writing.

During this work I have had assistance from the University of Helsingfors (Rosenberg's Travelling Bursaries Fund) and from Alfred Kordelin's General Trust for the Advancement of Progress and Knowledge, in Finland.

Christiania, February 1921.

Pentti Eskola.

INTRODUCTION.

The present writer recently proposed a classification of the crystalline rocks in several mineral facies[1], each of which comprises those rocks whose mineral composition is dependent only on the chemical bulk composition, while a definite chemical composition always results in the same set of minerals. Variations in the former are accompanied by parallel regular variations in the latter. It is assumed that the rocks belonging to a definite facies have originated under similar temperature and pressure conditions and have generally arrived at a state of equilibrium which appears to be independent of the mode of crystallization, either metamorphic or magmatic. To each metamorphic facies may thus be paralleled an igneous facies.

The main facies-groups of rocks hitherto proposed are the following:

Metamorphic facies	**Igneous facies**	Typical minerals
Sanidinite facies	*Diabase facies*	Sanidine, plagioclase, wollastonite, clino-enstatite-diopside, cordierite, sillimanite, tridymite and quartz.
Hornfels facies	*Gabbro facies*	Orthoclase, plagioclase, grossularite, wollastonite, diopside, enstatite, cordierite, andalusite (pseudostable?), quartz.
Greenschist facies	*Helsinkite facies*	Muscovite, albite, epidote, calcite, dolomite, talc, serpentine, chlorite.
Amphibolite facies	*Hornblende-gabbro facies*	Microcline, grossularite, wollastonite, diopside, hornblende-tremolite, anthophyllite, almandite, cordierite, sillimanite, muscovite.

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[1] Pentti Eskola, The Mineral Facies of Rocks. Norsk Geologisk Tidsskrift, 1920.

Metamorphic facies	**Igneous facies**	Typical minerals
Metamorphic eclogite facies	*Igneous eclogite facies*	Jadeite-diopside, enstatite, almandite-pyrope, cyanite.

Rather exhaustive treatises exist on the hornfels-facies in the contact-metamorphic rocks of the Christiania region by V. M. Goldschmidt and on the amphibolite facies in the metamorphic rocks in the Orijärvi region by the present writer. The sanidinite facies represents the same equilibrium conditions as those prevailing in the experimental research under atmospheric pressure.

The present paper endeavours to deal with the eclogite facies, as represented in the eclogites of Norway.

ON THE METHODS.

Facies-petrology is a study of the relations between the chemical and mineralogical composition of rocks. Attention, therefore, must be directed mainly towards the investigation of the constituent minerals, or the phases of the rocks.

Along with the bulk composition of a rock, its mineralogical composition, or the mode, must always be known. If possible, it should be known quantitatively, either estimated by geometrical methods, or by mechanical analysis by means of heavy solutions, or calculated from the rock analyses on the basis of qualitative microscopic examination. Sometimes the estimation of the mode may be difficult or impracticable, but in any case it must be hoped that no analyses of holocrystalline rocks will hereafter be published without at least a qualitative enumeration of all the minerals. An analysis without the statement of the minerals has absolutely no value for facies-petrology — and it has little value for modern petrology in general.

It is also very important that the enumeration of the minerals should refer to the same specimen as that on which the analysis has been carried out. Unfortunately this is not the rule in current petrographical works, and therefore the student of the laws of mineral paragenesis is often confronted with puzzling contradictions.

As the aim is to study mineral associations, it should be borne in mind that different incompatible associations may be contained in one and the same specimen, and therefore it should always be noted which minerals really occur in contact with each other. For in a stable association all the phases may be in immediate contact with each other.

As analyses of the rock minerals play a dominant rôle, their separation for analysis is of course of the greatest importance. This is rarely practicable by hand picking, in most cases heavy solutions must be used. Fortunately we now possess, in Clerici's solution[1], a liquid with which even the heavier rockmaking minerals, up to a specific gravity of 4.20, can be separated without any difficulty. I prepared this solution simply by neutralizing thallium carbonate with equivalent amounts of formic acid (85 pt) and malonic acid (concentrated aqueous solution) and by evaporating the clear solution obtained until a piece of almandite (sp. g. 4.0) floated.

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[1] E. Clerici, Preparazione di liquidi per la separazione dei minerali. Rend. R. Accad. dei Lincei (Classe di scienze fis.-mat.e nat.), 1907, 187—195. The original paper was not accessible to me, but a summary in F. Hörner's dissertation „Beiträge zur Kenntniss des Stauroliths", Heidelberg 1915, and in N. J. Min. 1908, II, p. 2.

In 1917, thallium carbonate cost, at Kahlbaum in Berlin, 110 Rmk per kilogram.

For the separation the rocks were crushed up in a diamond mortar and sifted, usually to a maximum diameter of 0.1 mm. The finest powder was now removed by washing with water, and after drying the first separation was made in a Brøgger funnel. The specific gravity of the liquid was determined, when the mineral in question just floated, and once more, when it just sank. These two values were not allowed to differ by more than 0.05. The average of them was taken as the specific gravity of the mineral. A second separation was always necessary before the mineral proved pure by examination under the microscope, and sometimes the grains must still be crushed up to effect separation of double grains or inclusions.

The separation of the minerals in most cases was combined with a mechanical analysis, or determination of the mode. Against this method could be raised the objection that the result may be affected by the removal of the finest powder by washing[1], as softer minerals will be pulverized more than the hard ones. I have not investigated how great errors may possibly result here, but probably they are not very grave. There are also other sources of error in this method, as the incomplete separation in consequence of double grains, mostly inevitable even in the finest grain practicable.

Where analyses of pure constituents are available, the analysis of the rock may often be omitted, the bulk composition of the rock then being calculated on the basis of the mode and the mineral analyses. This method was often practised in the course of the present work. The objection that the results may be unreliable owing to errors in the mechanical analyses is here of little importance, as in the case of the eclogites like so many other banded or schlieric crystalline rocks the relative amounts of the minerals itself are greatly variable. The figures obtained represent at all events the composition of a mixture of the constituent minerals, which in some parts of the rock must be present exactly in the proportions represented. The result may, moreover, be checked by calculating the specific gravity of the rock from those of its constituents in the mode, and comparing the result with the specific gravity of the rock directly determined. Such calculations have always shown very close agreement.

The determinations of the specific gravity of rocks were made in pieces of 100—500 g by weighing in air and water. Before weighing in air the pieces were dried during the night in vacuo and the air bubbles were removed by boiling at 30° under reduced pressure, the apparatus and the method being those proposed by V. M. Goldschmidt[1].

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[1] In one case the amount of the powder removed was determined to be 13 per cent.

Among the optical properties of the minerals, the indices of refraction have the greatest importance. For their determination I used a set of liquids prepared by myself after the directions of Mr. Olaf Andersen, according to the methods used in the Geophysical Laboratory of the Carnegie Institution of Washington.

In the case of the garnet the prism method was practised. Using grains of but 2 or 3 mm in diameter I could prepare four or five prisms at the same time, the whole procedure taking but half an hour.

J. Uhlig[2] proposed to designate the composition of the garnets with the molecular percentage figures of each of the simple compounds, as grossularite, andradite, almandite etc., each of which is expressed by the symbols of its most characteristic element.

Against this mode of designation it may be objected that, in the garnets, the bivalent elements are variable independently of the trivalent elements. It is not strictly correct to designate a garnet, in which enter MnO, CaO, Al_2O_3 and Fe_2O_3, as a mixture of spessartite, grossularite and andradite, as in such a mixture the Fe_2O_3 can not be said to be combined with CaO more than with MnO. Nor is it correct to calculate the percentages of the bivalent and the trivalent elements together to the sum of 100. I have therefore calculated the atomic percentages of the elements separately in each group of the isomorphic substituents. The designations thus resulting, e.g. $(Fe_{38}Mn_1Mg_{61})_3\,(Al_{97}Fe_3)_2$, are clear without any explanation, as they are simply molecular formulas, the group $(SiO_4)_{300}$ omitted, being common to all. Where no stress is laid on the trivalent elements which all except Al_2O_3, in the pyrope-almandite series, are of little importance, the garnets will simply be characterized by the bivalent elements, and a designation like $Fe_{82}Mn_7Mg_8Ca_3$ for a mixture of 82 mol. almandite, 7 mol. spessartite, 8 mol. pyrope and 3 mol. grossularite is as clear as it is simple. Thus we have a system of designations adaptable to any degree of accuracy and completeness needed.

In the determination of pyroxenes and olivines by means of refractive indices and other optical properties, F. Becke's compilation in C. Doelter's „Handbuch der Mineralchemie“[3], were adopted while for the monoclinic amphiboles Ford's diagrams were used[4].

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[1] Videnskapsselskapets Skrifter. I. Mat.-naturv. Klasse. 1916. No. 2, p. 4.

[2] J. Uhlig. Beitrag zur Kenntnis der Granaten in vulkanischen Gesteinen und Auswürflingen des Niederrheins. Verh. d. Nat. Ver. d. preuss. Rheinlande u. Westfalens. Bonn 1910, 67, 307—403.

[3] Band II, I, p. 1.

[4] W. E. Ford, A Contribution to the Optical Study of the Amphiboles. Am. Journ. Sci. XXXVII, 1914, p. 185.

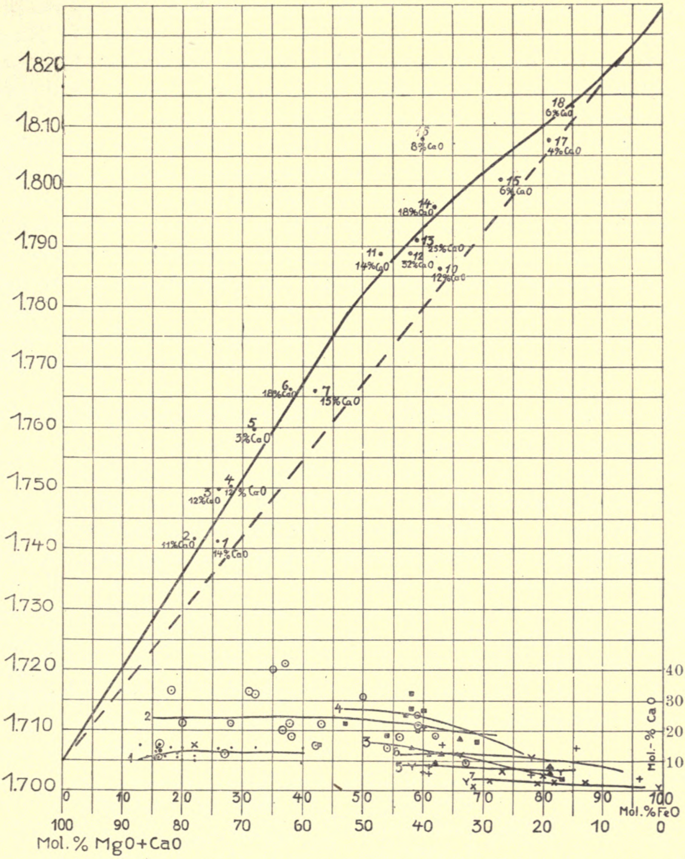

Fig. 1. The relation between the refringence and the composition in the pyrope-almandite garnets, and the variation in the quantity of lime in the garnets from different rocks. Garnets from: ● Olivine-rocks (1); ⊙ Eclogites (2); ▲ Gabbros (3); ■ Amphibolites (4); Y Cordierite-rocks (5); + Gneisses and micaschists (6); × Granites (7).

So much new material of garnet was gathered in the course of the work that it seemed reasonable to make use of this fresh evidence concerning the relations between the optical properties and chemical composition of the garnets. Those of my analyses made on pure material were compared with the analyses of pyrope and almandite garnets used by Ford[1]. To these ten analyses I could thus add eight new ones, which confirm the results and diagrams arrived at by Ford in the most remarkable manner. As they prove with full evidence, what Ford thought probable[1], that among his garnets those marked n:os 8 and 9 show such a great discrepancy with the others that either the analyses or the refractive indices must be erroneous, I omitted them entirely.

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[1] W. E. Ford, A Study of the Relations existing between the Chemical, Optical and other Physical Properties of the Members of the Garnet Group. Am. Journ. Sci. XL, 1915, p. 34.

With this improved material at hand an attempt was made to construct a diagram that could be used for determining garnets by means of the refringence. This was thought practicable by utilizing all the experience now gathered by me concerning the limits of solid solubility of the various compounds, the conditions of stability and the relations between the chemical composition of the garnets to the bulk composition and petrological characters of those rocks in which they occur.

The curve fig. 1 is based on the following material, all that are not my analyses (marked with *) having been taken from Ford's table (loc. cit.).

N:o	**Name**	**Locality**	**Composition**	**Index of refraction**
1.	Pyrope,	Kimberley,	$Fe_{26}Mg_{60}Ca_{14}$	1.7412
2.	Pyrope,	Colorado River,	$Fe_{22}Mg_{67}Ca_{11}$	1.7417
3*.	Eclogite-garnet,	Almklovdalen,	$Fe_{27}Mg_{61}Ca_{12}$	1.7498
4.	Pyrope,	Kimberley,	$Fe_{28}Mg_{60}Ca_{12}$	1.7504
5.	Rhodolite,	Mason Branch,	$Fe_{32}Mg_{64}Ca_{3}$	1.7596
6*.	Garnet from labradorite-rock,	Aurlandsfjord,	$Fe_{38}Mg_{44}Ca_{18}$	1.7658
7*.	Eclogite-garnet,	Silden,	$Fe_{42}Mg_{43}Ca_{15}$	1.7660
8.	Almandite,	Ceylon,	$Fe_{88}Mg_{4}\ Ca_{8}$	1.7779 (erroneous!)
9.	„	Jeypoor,	$Fe_{74}Mg_{12}Ca_{14}$	1.7815 (erroneous!)
10*.	Gabbro-garnet,	Meinkjaer,	$Fe_{63}Mg_{25}Ca_{12}$	1.7864
11*.	„	Aardal,	$Fe_{53}Mg_{33}Ca_{14}$	1.7887
12*.	Amphibolite-garnet,	Kantalahti,	$Fe_{58}Mg_{10}Ca_{32}$	1.7889
13*.	Eclogite-garnet,	Vanelvsdalen,	$Fe_{59}Mg_{16}Ca_{25}$	1.7911
14*.	„	Romsdalshorn,	$Fe_{62}Mg_{20}Ca_{18}$	1.7965
15.	Almandite,	Fort Wrangel,	$Fe_{73}Mg_{21}Ca_{6}$	1.8010
16.	„	Wittichen,	$Fe_{60}Mg_{32}Ca_{8}$	1.8078
17.	„	Salida,	$Fe_{81}Mg_{15}Ca_{4}$	1.8074
18.	„	Redding,	$Fe_{85}Mg_{9}\ Ca_{6}$	1.8132

Here we are concerned only with the garnets of the pyrope-almandite series. The percentage of MnO, always less than 2, was added to that of FeO, and the sum of (Fe,Mn)O, MgO and CaO was recalculated to 100 $^{0}/_{0}$. The continuous curve in the diagram expresses the relation between the ratio FeO : (MgO + CaO) and the refringence. The dotted line shows the same relation in pure mixtures of pyrope and almandite, according to Ford.

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[1] Loc. cit. p. 37.

The proportion of Fe_2O_3 to Al_2O_3 was not taken into account, firstly because the quantity of Fe_2O_3, in the series under consideration, is always small and little variable, and secondly because, an exact determination of FeO in the garnets being difficult though not impossible, most analyses of garnets are more or less unreliable in this respect.

As could be expected, the lime-bearing pyrope-almandite mixtures have higher refractive indices than those in which no MgO has been replaced by CaO. The difference is largest at about 60 pt FeO, owing to the fact that these garnets generally are richest in lime. The relation is not quite regular, however.

At first sight the refringence appears as a linear function of the ratio FeO : (MgO + CaO). Really it is not so, the apparent approximation being due to the fact that the amount of lime in mixtures varies with the variation of the ratio MgO : FeO. The latter, in turn, depends upon the bulk composition of the rocks and the attendant physical conditions, these interrelations being indeed the main subject of study in this paper. Now, both these factors, the physical conditions and the chemical composition, account for the actual characters of rocks. Therefore we will find, by grouping rocks in any system developed on a natural basis, that a definite group will contain garnets varying in composition between definite limits. This will be shown by the following table where the molecular percentages of the lime compound in the garnets in different rocks are given. The analytical material is mainly the same as used further on in this work. The garnets in the Norwegian labradorite-rocks have been treated as eclogite-garnets and not as gabbro-garnets, on grounds that will be obvious from the description.

Rock	Number of analyses	Mol. % of MgO-comp.	Average mol. % of CaO-compound	Average discrepancy	Maximum discrepancy
1. Peridotites and derivatives	17	75—61	11.7	1.5 mol. %	2.7 mol. %
2. Eclogites and related rocks	16	61—16	22.0	7.5 —„—	20.0 —„—
3. Gabbros and diorites	7	29—12	10.9	3.0 —„—	4.9 —„—
4. Amphibolites	8	28— 9	23.2	4.2 —„—	8.8 —„—
5. Cordierite-rocks	5	30—11	8.0	1.7 —„—	5.0 —„—
6. Gneiss and micaschist	7	33— 0	10.7	5.1 —„—	10.3 —„—
7. Granites	10	31— 7	3.9	1.5 —„—	2.9 —„—

In fig. 1 the molecular percentages of the lime-compounds in all these garnets have been plotted on the ordinates, the abscissas representing the ratio FeO : (MgO + CaO), as for the variation curve. Here the average percentages of the CaO-compound and their variation with the FeO : (MgO + CaO) ratios for the various rocks are shown by curves.

The pyropes in peridotites, serpentines, etc. have a very constant amount of lime. This is only due to a limited variation in the original material.

In the eclogite-garnets the amount of lime is more widely variable than in any other, owing to variable original material and specific physical conditions during their genesis. Therefore very little can be said with certainty about an eclogite-garnet on the basis of the refractive index. In the Norwegian eclogites, however, the variation is no greater than in the two following groups[1].

The garnets of all other rocks contain a prevailing amount of iron. The average amount of lime is largest in the garnets of the amphibolites and much smaller in those of the gabbros, apparently varying with the conditions obtaining during their formation. The still smaller quantities of lime found in garnets from the cordierite-bearing rocks and the granites may be ascribed to the composition of material available.

The group of gneiss and mica-schist again shows a greater average and maximum discrepancy from the average amount of lime than the other groups, excepting the eclogite. In this case this may simply be ascribed to the fact that this group is less homogeneous, comprising sedimentogenous and eruptivogenous schists and gneisses of various composition and facies development.

Practically, the diagrams in fig. 1 may be used in the following way. After having determined the index of refraction of a garnet either by the prism method or by the immersion method with liquids or melts, one finds the point on the curve corresponding to the (Fe,Mn)O : (MgO + CaO) ratio and, going downwards along the ordinates and selecting the proper diagram, the probable molecular percentage of CaO. The possible error in such determinations may be estimated on the basis of the above table and the diagrams. It must be noted that, in exceptional cases, the error may be greater than the maximum discrepancies named in the table.

All the other kinds of garnets but almandite-pyrope must, of course, be excluded. Spessartite garnets are always associated with other manganiferous minerals and lime-garnets with rocks rich in lime. In dubious cases chemical tests must be consulted. I preferably use the determination of FeO combined with a determination of refringence as a conclusive diagnostic of garnets.

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[1] I have therefore, in my studies, used the average lime-percentage of 6 analyses of Norwegian eclogite-garnet, being 18 mol. 0/0, the average discrepancy being 2.5 and the maximum discrepancy 7.0.

When the specific gravity can be determined, e. g. with the Clerici solution and a Westphal balance, Ford's triangle-diagrams may be used directly to determine the composition of the garnets. According to my experience with the rock-making garnets, no greater accuracy can be achieved by this method than by merely using the above refraction diagram, but it may, of course, be useful to check these results.

ECLOGITES IN NORDFJORD AND MØRE.

Petrological Sketch of the Gneiss Area in Nordfjord and Møre.

Introduction.

The eclogite-bearing gneiss area in western Norway comprises the northern part or the Nordfjord district of Sogn og Fjordane Fylke (formerly Nordre Bergenhus Amt) and almost the whole of the Møre Fylke (formerly Romsdals Amt) to which belong two districts: the southern called Søndmøre and the northern called Nordmøre.

This part of the Norwegian coast region is a highland cut by numerous deep fjords. It may well be spoken of as an elevated and re-eroded peneplain, and its geological architectonics are remarkably simple: all the vast masses of mountains belong to a deep-seated formation mainly consisting of igneous gneiss, within which occur numerous smaller masses ot olivine-rock, labradorite-rock and eclogite, in evident genetical connection with one another, and, moreover, crystalline limestone.

The first and so far the best geologic description of the gneiss area in Søndmøre and Nordfjord was given by H. Reusch in 1877[1]. The geological map (fig. 2) is, in part, a copy of that accompanying the treatise just quoted, and in part drawn according to J. H. L. Vogt[2] and the occurrences of limestone according to C. Bugge[3]. My own observations on the occurences of eclogite, olivine-rock and labradorite-rock have also been utilized.

The gneiss.

The gneiss of Nordfjord and Møre really presents a series of structural varieties from a non-foliated coarse-grained porphyritic granite through augengneiss to different kinds of foliated gneiss, as e. g. veined gneisses or arterites, fine-grained, schistose mica-gneisses, often with almandite, and mylonitic gneisses. Such augengneisses showing marked granitoid structure have, in Norwegian literature, been called gneiss-granite.

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[1] H. H. Reusch, Grundfjeldet i Søndre Søndmøre og en del av Nordfjord. Forhandlinger i Videnskapsselskapet i Christiania 1877.

[2] J. H. L. Vogt, Olivinstenen i indre og søndre Søndmøre. Nyt Magazin for Naturvidenskabene, 1883.

[3] C. Bugge, Kalksten og marmor i Romsdals amt. Norges Geol. Undersøgelse, Aarbog 1905, VI.

We shall at first give a few examples of the petrographical characters of the gneisses.

Gneiss-granite from the island Silden, Selje. A porphyritic granite whose phenocrysts, two or three centimeters long, are somewhat drawn out into lenticular eyes. They consist of crosshatched microcline containing much oligoclase as perthitic threads. The ground-mass, fine in grain and with serrated boundaries between the constituents, is composed of microcline, oligoclase, quartz, biotite, epidote and zoisite, and chlorite. The oligoclase, in sections $\perp$ M, shows extinction almost parallel to the trace of M. The biotite, dark brown in colour, occurs as groups of parallel fine scales among which also occur grains of zoisite with border zones of epidote. The refractive indices of the components of this homoaxial intergrowth show the following relation: γ epidote $>$ γ zoisite and α epidote $<$ α zoisite.

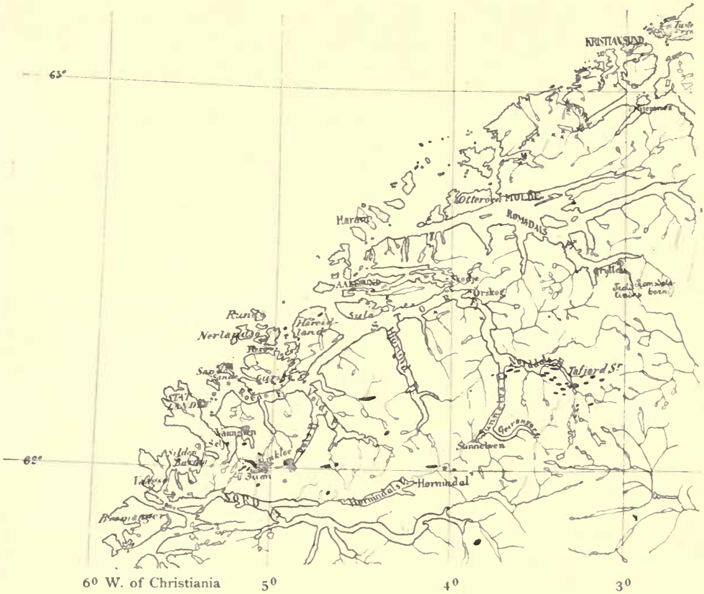

Fig. 2. Map of parts of Nordfjord and More. White = gneiss; black = olivine-rock; dotted = eclogite; shaded = labradorite-rock; crosses = limestone.

Augengneiss from Vederhus, Selje. This rock is megascopically a gneiss-granite, but its phenocrysts have in part been granulated into a very fine mass of microcline. The ground-mass also is fine, though the aggregates of quartz are a little coarser in grain than the microcline and oligoclase. Frequent minute groups of myrmekite are present in the ground-mass. Epidote and octahedra of magnetite are associated with the biotite, and muscovite also occurs.

Augengneisses from numerous other localities showing the same mineralogical and structural characters as the two specimens described were studied, and we may state that these examples represent characteristic types of the gneiss-granite on Nordfjord and Møre. Frequently the eyes have been granulated altogether. In some examples there occur also smaller eyes of oligoclase. The occurrence of epidote along with the biotite is persistent, while chlorite is rather rarely present.

Many exposures well illustrate the development of veined gneisses from such augengneisses. I studied the phenomenon at Maurstad near Bryggen in Nordfjord. Here occurs an augengneiss whose eyes, in the most granite-like variety, have been drawn out in length, but, at right angles to the elongation, show almost equidimensional sections. Along certain flexures (fig. 3) the eyes have been flattened out and present small veinlets of feldspar. Apparently such flexures have originated before the complete consolidation of the rock. The aplitic primary dikes seen here have not been subjected to structural deformation at all, though they have been thinned out.

On the shore-rocks between Bryggen and Totland, and likewise on Mandseidet in Selje, the development of the original phenocrysts could be followed in further stages: They have been drawn out into long thin bands and become granulated. At the same time they have continued to grow further, and not only microcline but also quartz and plagioclase have crystallized in the groups that originally were phenocrysts of microcline. The interspaces between these veins become more and more enriched in biotite which assumes a parallel arrangement and thus, by a kind of crystallization differentiation, a veined gneiss has been gradually developed.

The leucocratic veins and bands originated in the manner just outlined may attain considerable dimensions and they often have been folded in curious ways.

Other kinds of inhomogeneity and schlieric development frequently originated by assimilation or re-fusion of basic segregations crystallized earlier than the main gneiss. There are, however, in the tracts that I myself visited, no examples of basic fragments of truly alien siliceous rocks in the gneisses, although the limestones enclosed in the gneiss-masses may be of a sedimentogenous origin and the gneiss in their vicinity may contain assimilated materials derived from ancient sedimentary rocks. Mainly, the gneiss of Nordfjord and Møre is altogether an igneous rock.

We shall add short petrographic descriptions of a few examples of veined and banded gneiss.

Veined gneiss from Blaafjeld, Kleiven at Geiranger, Søndmore. The rock, as a whole, is rather leucocratic and of a beautiful light red colour. The lighter as well as the darker, biotite-bearing, bands are very thin, but there is no parallel arrangement of any of the constituents, nor any mechanical deformation. The constituents are microcline, quartz, oligoclase, biotite, muscovite, magnetite (as octahedra) and orthite as megascopic grains. Both perthite and antiperthite occur, and plagioclase-quartz-myrmekite is abundant.

Almandite-gneiss from Grytingen, Selje, occurring as a homogeneous band a few meters thick. This rock contains much quartz and, as the second in quantity, oligoclase. Dark brown biotite and an optically uniaxial colourless mica are almost equal in amount. The biotite contains minute zircons with pleochroic halos. Large prisms of apatite and still larger crystals of almandite, almost free from inclusions, complete the list of minerals. Potash felspar is absent.

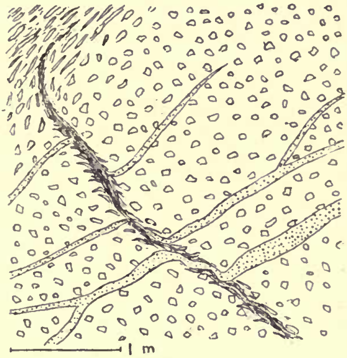

Fig. 3. Augengneiss, passing over into "veined gneiss", with dikes of aplite (dotted).

Oligoclasite from Bleieskarsvand, Syvde, Søndmøre. In this connection may be mentioned a rock showing some approximation towards the labradorite-rocks, though perhaps more closely related to the gneiss. The specimen studied has been collected by H. Reusch, and I do not know its mode of occurrence. It is chiefly composed of plagioclase, in sections ⊥ PM showing extinction angles of + 9° corresponding to the composition Ab_{72}. Quartz occurs only as minute rounded inclusions, and potash feldspar as antiperthitic particles. Other minor constituents are biotite, apatite and chlorite. The structure is non-foliated.

Such an oligoclasite might well be supposed to have originated as a band by the differentiation by crystallization under stress. True labradorite-rocks often occur in the same manner as bands in the gneiss, and appear to have crystallized later than the darker schliers of the mixed country-rock. Such is an occurrence on Aasnaesnakken near Bryggen, Nordfjord. The light band is a few meters thick, and is composed of a plagioclase with 60 pt Ab, besides hornblende, biotite and abundant epidote. In spite of resemblance in the mode of occurrence, it is difficult to understand this and other similar rocks as direct differentiates from the gneiss in the above manner, as their composition shows such a strange and persistent character.

Mylonitic gneiss from Vanelven. From the shore-rocks near Torsvik in the parish of Vanelven I collected specimens of extremely mylonitized gneiss, in part derived from an augengneiss and in part from banded even-grained gneiss. As usual, this gneiss shows a marked stretching, the axis of which pitches to the East. Going westwards the rock grades over into an even-grained gneiss free from mechanical deformation.

The mylonitization means deformation of a solid rock. It is a very common phenomenon, though always of a very limited extent. As was the case in the above example, the strongest mylonitization always occurs in rocks that have suffered strong protoclastic influences. The stress apparently still continued to act after the consolidation had ended, but now its action was limited to certain shearing-planes, the largest parts of the solid rock-masses resisting the stress.

The Limestone.

Occurrences of crystalline limestone are fairly numerous within the gneiss area of Nordfjord and Møre (cf. fig. 2). The limestone is generally coarsely crystalline and, according to C. Bugge (loc. cit. p. 16), contains the following accessory minerals: Quartz, scapolite, white mica, plagioclase, apatite, sometimes also garnet, pyroxene, hornblende, biotite and green mica, occasionally pyrite, graphite and iron ores.

The rocks bounding the limestone are, in most cases, said to consist of hornblende-gneiss, often garnet-bearing.

I have myself only visited the limestone of Breivik and Saude near Larsnes, Gurskø. The rock there occurs as a very pure layer in almost vertical position more than 100 m in breadth. Smaller lenticular layers are embedded in the adjacent gneiss. The immediate contact of the limestone is marked by a "contact-wall" that was found to consist of coarse-grained diopside and microcline. The country-rock, in its megascopic features, conforms to the descriptions of the hornblende-gneiss, given by Reusch and Bugge. It is a banded or veined rock, with alternating white "veins" and duller portions containing elongated prisms of a mineral that was believed to be hornblende. By a microscopic examination of a specimen collected from Larsnes, more than one km west of the limestone, I found, however, that this rock is composed of green pyroxene (diopside with a little aegirite) and plagioclase (oligoclase) besides small amounts of biotite and titanite. I have not extended my work to any closer investigation of this very remarkable rock and cannot say whether such plagioclase-diopside rocks have a wide-spread occurrence in the Møre gneiss area. Probably they are limited to the vicinity of the occurrences of limestone.

The petrology of the limestones and its country-rocks in Møre affords many problems of great interest which still remain to be cleared up by detailed field and laboratory work. Compared with the occurrences of limestone in the Archaean of Finland they present a striking difference in being embedded immediately in formations of a highly crystalline gneiss. No bedded and laminated leptites or other apparent "supercrustal", volcanogenous or sedimentogenous, rocks can be traced here. If the limestones have originally been sedimentary beds, they have, during the diastrophism, been pressed down in the eruptive gneiss magma, and their country-rocks have lost all their original characters.

On Gurskø no eclogites occur in immediate contact with the limestone. J. H. L. Vogt[1] records an occurrence of "eclogite near marble" from Brandsaeter near Kornstadfjord. I had a specimen from this locality collected by Prof. Vogt. Its garnet showed $n_{Na} = 1.7525$ and was found to contain 17.77 % FeO and 8.06 % CaO, conforming to the composition $Fe_{51}Mg_{19}Ca_{30}$. The specific gravity of the rock is 3.440. Thus it is a true eclogite, and has not assimilated any materials from the limestone. Probably there exists no genetical connection whatever between the eclogites and limestones.

The Olivine-rock or Dunite.

Numerous lenticular bodies of olivine-rock form the largest and most conspicuous inclusions in the gneiss of Nordfjord and Møre. Their mode of occurrence and stratigraphical relations to the gneiss have been carefully studied by H. H. Reusch[2] and J. H. L. Vogt[3]. From these surveys the lenses and the foliation of the rock always appear to be conformable to the strike and the band-structure of the adjacent gneiss. The occurrences in Almklovdalen have been folded together with the surrounding gneiss. Largest of all are the occurrences in the region of Tafjord-Sunelvsfjord in Søndmøre and Hornindal in Nordfjord. The rock bodies in the former region form several lenses, some 2 kilometers in maximum breadth, arranged one after another in a narrow zone that may be followed over 20 kilometers along the strike. In Hornindal a single lens attains a length of 12 kilometers.

Reusch, Brøgger, and Vogt have all arrived at the conclusion, that the olivine-rocks of Nordfjord and Møre belong as integrating members in the Archaean metamorphic formation, to which also belongs the gneiss. The olivine-rocks are not by any means intrusive in the gneiss, but they are contemporaneous and both have the same origin, whatever it may have been. This opinion was especially emphasized with great eloquence by W. C. Brøgger[4] who concluded with the following words: "Man könnte wohl

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[1] J. H. L. Vogt, Norsk marmor. Norges geologiske undersøkelse 22, 1897.

[2] Loc. cit. (Forhandl. Vid.-selsk. i Christiania, 1877) and: Nye Oplysninger om Olivinstenen i Almeklovdalen og Sundalen paa Søndmøre. Ibid. 1883.

[3] Loc. cit. (Nyt Mag. Naturvid., 1883.)

[4] W. C. Brøgger, Ueber Olivinfels von Søndmøre. Neues Jahrb. f. Min. etc., 1880, II, p. 192.

ein Buch voll schreiben ohne dabei klüger zu werden; denn die wahre Grundlage für die Diskussion fehlt, — solange man sich in der jetzigen Unwissenheit über die Bildung der krystallinen Schiefer befindet. Wenn es sich vielleicht einmal herausstellen wird, dass dieselbe von derjenigen der älteren Eruptivgesteine nicht so weit verschieden sei, dann dürften Gesteine wie die krystallinischen Olivinschiefer vielleicht auch leichter zu verdauen sein."

At present we regard the gneiss as an intrusive rock. The conclusions of the first Norwegian investigators nevertheless are wholly valid as regards the close connection of the olivine-rocks with the gneiss. Both have the same mode of origin and both are igneous rocks with a primary mineral composition.

As evidences of the primary, non-metamorphic character of the olivine-rock we may name the absence of every relict feature, and the structure of the varieties containing other minerals than olivine: they are true igneous differentiates apparently originated by the crystallization of their actual minerals.

This olivine-rock is an igneous rock, a dunite. It is a member of the Norwegian peridotites, on which C. W. Carstens[1] recently started a series of investigations.

The olivine-rocks are not younger than their country-rock, their consolidation has taken place rather earlier, but there is probably no great difference in age. This interpretation of the genetical relations holds good no matter whether the gneiss-formation is regarded as being of Archaean or of post-Archaean age.

For the earlier investigators the conformable stratigraphy and the absence of evidences of intrusion were the most weighty arguments in favour of a common origin of the gneiss and the olivine-rock. From the present stand-point, regarding the rocks as a series of magmatic differentiates, these proofs are not quite sufficient, as many intrusive masses also show conformable boundaries and absence of intersecting veins, enclosed fragments etc. For me the decisive evidence lies in the protoclastic or primarily foliated character of the whole gneiss formation. Thus, when the olivine-rock allots itself to the same unit, its intrusion and foliation prove to be results of the same process of folding and intrusion. Later we shall pay attention to the evident connection of the olivine-rocks with the eclogites, and it will appear that both kinds of inclusions are of an earlier consolidation than the gneiss.

The olivine-rock in Almklovdalen, Vanelven, Søndmore. A petrographic description of the olivine-rock of Almklovdalen was given by W. C. Brøgger (loc. cit., 1880). The rock of this locality is, for the greater part, a very pure and unaltered olivine-rock of even and medium grain. On Skjaelhammeren and in Sundalen a variety occurs containing large translucent crystals of olivine, first described by Reusch (loc. cit. 1877). Brøgger regards these crystals as phenocrysts and compares them with the phenocrysts of labradorite sometimes found in porphyritic labradorite-rock. Brøgger has made an analysis of such a nodule which is quoted below I. Under II is quoted an analysis of the olivine-rock from Almklovdalen, published by U. Grubenmann[1].

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[1] C. W. Carstens, Norske peridotiter, I and II. Norsk Geologisk Tidsskrift, V, 1918.

	I	II
SiO_2	38.87	41.83
Al_2O_3	—	0.51
Cr_2O_3	—	0.38
Fe_2O_3	—	0.82
FeO	8.45	3.88
MnO	0.12	tr.
MgO	51.86	48.54
CaO	0.99	0.25
H_2O	—	0.54
	100.29	99.75
Sp.g.	3.32	3.27

The rock is markedly schistose, in part due to a stretching out of the grains of olivine and in part to flakes of pale green chlorite and occasionally a colourless mica present in small amounts and arranged parallel. Another mineral very frequently present, either together with enstatite or alone, is a colourless monoclinic amphibole. Brøgger regards it as smaragdite, but to me it seems more probable that it is cummingtonite. I found, in a specimen marked "Almklovdalen": $c : \gamma = 18°$, $2V\ \gamma = 75°$ appr. The positive optical character conforms with the cummingtonite, while the tremolite-actinolite is optically negative. The percentage of lime in the olivine-rock analyzed is far too low to allow the assumption that lime-amphibole should have formed. Still the rock invariably contains chromite.

Olivine-enstatite-rock or saxonite. The olivine-rock in Almklovdalen frequently contains some enstatite which in places becomes a chief constituent and may be more abundant than the olivine itself. Such olivine-enstatite-rock or saxonite seems to be confined to the marginal parts of the occurrences and is especially common in the smaller isolated masses around the large lenses. I collected specimens of it from Gaateranden and Sortegølen near Kasen and from two small occurrences west and south of Duestøl. At the last-named locality the rock grades over into an enstatite-rock free from olivine. The enstatite occurs in the form of coarse prisms, one or two centimeters long.

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[1] U. Grubenmann, Die Kristallinen Schiefer, 1910, p. 224.

Pyrope-diopside-olivine-rock is found at a few points in the central parts of the larger masses of dunite, where eclogitic segregations also occur. The rounded crystals of red pyrope, about 0.5 cm in average diameter and surrounded by a kelyphite-shell, and equant crystals of emerald-green chrome-diopside of the same size are evenly scattered in the much finer ground-mass of olivine, and in addition occur some crystals of enstatite.

In a specimen of pyrope-diopside-olivine-rock from Lien I determined some optical constants of the minerals.

Olivine: $\beta = 1.670 \pm 0.001$. $2V\gamma = 85°$ appr.

Composition: $Fo_{90}Fa_{10}$.

Pyrope: $n = 1.742 \pm 0.002$.

Composition: $Fe_{23}Mg_{65}Ca_{12}$.

Chrome-diopside: $\beta = 1.678 \pm 0.002$.

Composition probably nearly identical with the pyroxene from the eclogite of Almklovdalen (cf. analysis p. 28), though with more chromic oxide.

Enstatite: $\gamma = 1.670 \pm 0.002$.

Composition apparently nearly identical with that of the enstatite from Almklovdalen with 5.20 % FeO in which K. Johansson[1] determined

$$\alpha_{Na} = 1.6607;\ \beta_{Na} = 1.6658;\ \gamma_{Na} = 1.6715.$$
$$2V\gamma = 76° 54'.$$

All these varieties of dunite and saxonite are very constant types of rocks, and in various occurrences in many lands their minerals show the same characters and have the same composition. But in the absence of every trace of serpentinization the best preserved dunite in Almklovdalen is almost unique in the whole world.

As Reusch points out (loc. cit. 1877), serpentinization occurs in the occurrences in Almklovdalen mainly near the boundaries of the masses. The same writer proved by microscopic examination and comparison with surface-specimens exposed to the atmospheric agencies, that this alteration has nothing to do with the weathering. From the facies theory it is apparently a posterior change impressed upon the rock on its way towards the earth's surface. Its character tells us about the conditions of the greenschist facies.

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[1] K. Johansson, Bihang till K. Vet. Akad. handl. Stockholm 17. N:o 4, 1891. Ref. in Zs. Kr. 23, 152.

Many local mineral developments within olivine-rock masses also bear evidence of conditions under which hydrated minerals were formed. To this group of phenomena belongs the alteration of the eclogitic nodules in the olivine-rock into chlorite, talc, and epidote. Lumps and lenses or veins of talc are common, and associated with this mineral occur chlorite, biotite-like mica and carbonates.

At other places the amphibolite facies has locally developed in the form of either cummingtonite or anthophyllite. H. Reusch recently described an occurrence of anthophyllite-asbestos near Berget in Almklovdalen[1]. The anthophyllite occurs there in the form of a dike in the olivine-rock.

Other occurrences of olivine-rock in Nordfjord and More. In the numerous other occurrences of dunite and saxonite in the area considered the petrographical characters of the rocks are nearly identical with those in Almklovdalen, though such a perfect degree of preservation is rare. Olivine-rock free from garnet or pyroxene is probably most common, but saxonites containing much enstatite are also widely distributed.

Saxonite with dominant enstatite has been met with at Sørpol in Selje (Reusch) and west of Saude near Larsnes, Gurskø (Eskola). Enstatite and olivine almost equal in amount are met with in the rock of Hovden in Hornindal, Nordfjord (Reusch) (with cummingtonite) and in Sølvbergknausen near Stensvik, Søndmøre (Eskola).

Pyrope-diopside-olivine rock has, except for the occurrences in Almklovdalen, only been recorded by J. H. L. Vogt (loc. cit. 1883) from the vicinity of the occurrences of eclogite near Tafjord, Nordalen, Sondmore.

The Labradorite-rock.

The labradorite-rock occurs, in the gneiss-area, much in the manner of other light bands in the gneiss, but the bands of this rock, homogeneous in composition and structure, may attain much greater breadth than the light gneiss bands. I have found bands of labradorite-rock but a few meters thick, and the largest observed measure a few hundred meters.

At the boundaries they prove to be younger than the gneiss, enclosing fragments and intruding into the gneiss as veins almost parallel to the strike.

Labradorite-rock has so far only been met with in tracts where olivine-rock and eclogite occur, and in most cases the connection between these three kinds of rocks is strikingly close. These relations will be discussed in the chapter dealing with the eclogites.

Labradorite-rock from the mountains east of Ekremsaeter in Almklovdalen. This occurrence affords an example of labradorite-rock typical of the gneiss area in Nordfjord and Møre. It is a sill-formed mass in the gneiss striking N 75° W, in vertical position, and was followed about 1 kilometer along the strike with a breadth of about 200 meters. Gneiss bounds it on both sides, and flakes and schliers of gneiss may be seen enclosed in the rock. On the northern side, eclogite crops out at many points in contact with the labradorite-rock, and, towards the west, the labradorite-rock strikes in the direction towards the largest mass of olivine-rock in Almklovdalen (cf. fig. 2).

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[1] H. Reusch, En asbestforekomst i Vanelven. Norsk Geologisk Tidsskrift V, 1918, p. 95.

The rock is distinctly banded, chiefly owing to an unequal distribution of its dark constituents. Along the strike are arranged many dikes of labradorite-pegmatite, at times, however, intersecting the banding.

This labradorite-rock is mainly composed of labradorite, in sections ⊥ PM showing extinction angles of 30°, corresponding to about $Ab_{45} An_{55}$. A faint zonal structure may be observed. Besides the plagioclase there are small amounts of dark green hornblende, whose amount does not exceed 5 pt of the rock mass, and quite trifling amounts of black iron-ore, epidote and chlorite.

The average grain of the labradorite is about 0.6 mm, but there are more fine-grained bands along the strike. Zoisitization does not occur.

The structure of the labradorite-rock might be called aplitic, all the grains being equally xenomorphic. Protoclastic changes, on the other hand, are apparent. The hornblende, as homogeneous individual prisms, is idiomorphic on the prism zone. There is nothing to point to a secondary origin or uralitic character, and we must conclude that, if pyroxene has ever existed in this rock, it may have been resorbed already during the consolidation and the hornblende crystallized out instead of it.

Most of the other occurrences show characters strictly similar to the above example, but there may be considerable variation even in a single mass. Thus, of three specimens collected from the occurrence near the Almklov farm, one has a plagioclase varying from Ab_{57} to Ab_{50} with at least one third of its mass consisting of intergrown potash feldspar (orthoclase, showing parallel extinction in sections ⊥ M), and besides much clinozoisite in large crystals bordered by zones of epidote, and biotite, but no hornblende. Another specimen has plagioclase from Ab_{60} to Ab_{46} with much epidote, but no potash feldspar nor dark minerals, while a third, taken from the contact against the gneiss, has a plagioclase Ab_{48} and a pale green hornblende with biotite.

In a specimen from Skyrfjeldet on Sandø the plagioclase is anorthitic, varying from Ab_{82} to Ab_{10}. The grains have rather rectilinear outlines and the structure is therefore pavement-like.

In the following list are quoted the compositions of the plagioclase from all the occurrences studied. All the determinations have been made on sections ⊥ PM.

The Almklov farm, Almklovdalen	Ab$_{60}$—Ab$_{46}$	
East of Ekremsaeter, —„—	Ab$_{45}$	
Near Gusdalsvand, —„—	Ab$_{65}$—Ab$_{54}$	
Fiskaa, Vanelven	Ab$_{50}$	
Dansen near Dalsfjorden	Ab$_{54}$—Ab$_{50}$	
Stensvik —„—	Ab$_{55}$—Ab$_{45}$	
Tafjord, Nordalen	Ab$_{50}$	
Seljenaes, Selje	Ab$_{72}$—Ab$_{45}$	(Much zoisite)
Aasnaesnakken, Bryggen	Ab$_{60}$	—„—
Frøisaeter, Utviken, Nordfjord	Ab$_{75}$—Ab$_{40}$	—„—
Skyrfjeldet, Sandø	Ab$_{32}$—Ab$_{10}$	

Disregarding such cases where much zoisite has been developed the composition of the labradorites is rather constant, between Ab$_{45}$ and Ab$_{60}$. Great variation is almost invariably combined with the development of inverse zonal structure, very marked in the rock from Seljenaes that will be described later, and e. g. in the specimen from Frøisaeter, Utviken. The latter is a fine-grained mylonitic variety with the average diameter of the plagioclase about 0.1 mm and much larger prisms of zoisite. I measured the extinction angles in three grains cut $\perp$ PM:

(1) border 30°, kernel 6°
(2) „ 28°, „ 18°
(3) „ 32°, „ 7°

In the specimen from Gusdalsvand inverse zonality occurs in a rock free from zoisite minerals; thus the phenomenon is not connected with saussuritization. In other cases a faint normal zonality was observed, as in the specimens from Dansen near Dalsfjorden.

It is hard to find any valid explanation for the inverse zonal structure in this case.

We may summarize our observations on the labradorite-rock in Nordfjord and Møre by comparing it with the labradorite rocks of the Bergen and the Sogn regions. The present rock differs from the latter: (1) in having amphiboles instead of pyroxenes; (2) in being more distinctly foliated in structure and finer in grain; (3) in the smaller dimensions of its intrusions. In the bulk composition, however, there is no notable general difference, and a further similarity obtains in the occurrence of garnet-bearing varieties and gradations into eclogites in both.

The eclogite.

Literature.

1. H. Möhl, Die Eruptivgesteine Norwegens. Nyt Magazin for Naturvidenskaberne 1877.

2. H. H. Reusch, Grundfjeldet i søndre Søndmøre og en Del af Nordfjord. Forhandlinger i Videnskapsselskabet i Christiania 1877.

3. E. R. Riess, Untersuchung über die Zusammensetzung des Eklogits. T. M. P. M., I, 1878.

4. Th. Kjerulf, Udsigt over det Sydlige Norges Geologi, 1879.

5. W. C. Brogger, Ueber Olivinfels von Søndmøre. Neues Jahrb. f. Min., Geol. u. Pal. 1880. II.

6. J. H. L. Vogt, Olivinstenen i indre og søndre Søndmøre. Nyt Magazin for Naturvidenskabene, 1883.

7. H. H. Reusch, Nye Oplysninger om Olivinstenen i Almeklovdalen og Sundalen paa Søndmøre. Forhandlinger i Videnskapselskabet i Christiania, 1883.

8. Th. Kjerulf, Beskrivelse av en Række Norske Bergarter. Universitetsprogram 1861.

The occurrences.

The vast area of gneiss in Nordfjord and Møre being still very imperfectly explored geologically, the number of occurrences of eclogite as well as of dunite and labradorite-rock will certainly be found to be much larger than is known at present. This is especially true as regards the eclogites which, in many parts of the area, are exceedingly common as small lenses enclosed in gneiss. In the interest of future investigation it may, however, be useful to give a list of all the occurrences of eclogite observed. The figures within parentheses refer to the above bibliography and the names of persons to collectors of specimens of eclogites kept at the Geological Museum in Christiania and at Bergens Museum (the collections of C. F. Kolderup).

The parish of Daviken, Nordfjord: Bryggen and very numerous localities in its neighbourhood, e. g. Aasnaes, Maurstad, Nore, Aaland, Totland, Rimestad (2; H. Reusch, M. Irgens and Th. Hiortdahl, Eskola).

The parish of Selje, Nordfjord: Vaagsø (P. Schei), Saltkjael and Maaløy (H. Reusch, Eskola), the islands of Silden and Barmen (H. Reusch), Gangeskar, Lyngenes and Osmundvaag near Sørpol (H. Reusch), Seljeø (2), Seljenaes near Nordpol, Ersholmen, Grytingvaag, Hamre, Listo and Kjøde (Eskola).

The parish of Vanelven, Søndmore: Rødhaugen and Lien (2, 6, 7; H. Reusch, Eskola), Duen (2, 3, 6, 8; M. Irgens and Th. Hiortdahl, Eskola), Almklovsaeter and Gusdalsvand (6, Eskola), E. of Ekremsaeter, Sortegølen near Kasen, Tuen, Aahjem (Eskola), Hellebust (C. F. Kolderup).

Gurskø, Hareidlandet, Bøland, Bergsø, Nerlandsø, Remø, Sandø, Kransø (many occurrences on each of these islands on the coast of Søndmøre; 2; H. Reusch, C. F. Kolderup).

The parish of Dalsviken: Sølvbergknausen, Omelfot (Eskola) and Westbakken, Stensvik (C. F. Kolderup).

Søndre Vartdal (2; H. Reusch).

Sulø near Aalesund (8; Th. Kjerulf).

Kalskaret between Tafjord and Herdalen, Søndmøre (6; J. H. L. Vogt).

Søholt Mine near Ørskog (8; Th. Kjerulf).

Romsdalshorn, Gryten, Runeberget and Stordal near Romsdalsfjord (1, 3, 4, 8; Th. Kjerulf).

Langeland near Hellesylt, Sunelvsfjord, Søndmøre (H. Reusch).

Haram, Nordmøre (Th. Kjerulf ?).

Gimnaes S of Kristianssund. Nordmøre (3, 8; Th. Kjerulf).
Hegerskjaeret in Hustadviken and Trekrem near Tingvold, Nordmøre (Th. Kjerulf).
Saksnaesodden in Halsefjord, Nordmøre (Th. Kjerulf ?).
Rofjeldets Hammere near Rovand, Hevne, Nordmøre (Hauan).
Brandsaeter near Kornstadfjord, Nordmøre (J. H. L. Vogt).
Halsnaes, Tusteren, Nordmøre (Hauan).

Quantitative Investigations on the Eclogites.

Within the areas of granitic gneiss in Nordfjord and Møre eclogite occurs in two manners: 1) as lenticular masses in the gneiss and 2) as bands or lenses in the olivine-rock.

The eclogites occurring in the masses of olivine-rock are quantitatively very inconspicuous and rather present the appearance of aggregations of the garnet and pyroxenes, found as accessories in the main rock. When going to investigate the chemical composition of the minerals one finds, however, that they are more independent than could be supposed from the appearance: the garnets are not chemically the same as those in the country-rock, but are richer in iron. On the other hand, they show chemical characters clearly pointing to a close genetic connection with the olivine-rock: they are poor in alkalies and rich in chromic oxide. Mineralogically these segregations in the olivine-rock show a great variation, almost all the possible combinations of the four minerals olivine, enstatite, diopside and garnet being represented, though the combination diopside—garnet (eclogite) is most common.

The eclogites enclosed directly in gneiss are greatly variable in their chemical and mineralogical composition as well as in structure. From the segregations in the olivine-rock they differ in being almost free from chromic oxide and containing considerable quantities of alkalies.

The eclogite from Rødhaugen, Almklovdalen, Søndmøre.

As an example of an eclogite in olivine-rock I examined quantitatively a specimen marked "Almklovdalen". A comparison with specimens later collected by myself made it certain that it had been taken from the hill called Rødhaugen.

The minerals being unaltered and free from inclusions, samples could be prepared for analysis simply by picking out clean grains. The sample of garnet thus obtained proved at once to be pure, and the same was the case with the pyroxene, which, however, was also treated with the heavy solution.

The analysis of the garnet, made by the writer, gave the following results:

	0/0	Mol. numb.	
SiO_2	41.52	691	691
TiO_2	tr.[1]	—	
Al_2O_3	23.01	225	234
Cr_2O_3	0.22	1	
Fe_2O_3	1.22	8	
FeO	12.86	179	683
MnO	0.33	4	
NiO	0.00	—	
MgO	16.64	416	
CaO	4.71	84	
Na_2O	0.00	—	
K_2O	0.00	—	
H_2O	0.16	—	
	100.67		
Sp.g.	3.782		

$n_{Na} = 1.7498$

$RO : R_2O_3 : SiO_2 = 2.92 : 1 : 2.95$

The composition of the garnet: $(Fe_{26}Mn_1Mg_{61}Ca_{12})_3(Al_{97}Fe_3)_2$.

The analysis of the pyroxene, made by the writer, ran out as follows:

	0/0	Mol. numb.
SiO_2	54.49	905
TiO_2	tr.[1]	—
Al_2O_3	2.50	25
Cr_2O_3	0.20	1
Fe_2O_3	1.63	10
FeO	1.98	28
MnO	0.06	1
NiO	0.03	—
MgO	16.74	418
CaO	21.40	382
Na_2O	0.83	13
K_2O	0.40	4
H_2O	0.12	—
	100.38	
Sp.g.	3.30	

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[1] Less than 0.10 0/0.

β_{Na} = 1.675 ± 0.002.
$2V\gamma$ = 58° (determined with a net-ocular)
= 59° (determined with a Becke drawing table)
$c : \gamma$ = 40° appr.

This analysis may be calculated as follows:[1]

		Jadeite (Na,K) (Al,Fe) Si_2O_6	Tschermak's silicate (Mg,Fe) (Al,Fe) SiO_6	Diopside (Mg, Fe) Ca Si_2O_6	Enstatite (Mg, Fe) SiO_3	Excess
SiO_2	54.49	4.08	1.08	45.96	2.76	0.61
Al_2O_3	2.50	1.23	1.27			
Cr_2O_3	0.20	0.20				
Fe_2O_3	1.63	0.64	0.99			
FeO	1.98					
MnO	0.06		0.14	1.80	0.13	
NiO	0.03					
MgO	16.74		0.64	14.32	1.78	
CaO	21.40			21.40		
Na_2O	0.83	0.83				
K_2O	0.40	0.40				
H_2O	0.12					0.12
	100.38	7.38	4.12	83.48	4.67	0.73

Diopside	83.48
Jadeite	7.38
Enstatite	4.67
Tschermak's silicate	4.12
Unaccounted for	0.73
	100.38

The specific gravity of the rock was found to be 3.510 (t = 13°). The rock being practically bimineralic, its mode could be calculated from this value and the specific gravities of the minerals:

Pyroxene	55.16 %
Garnet	44.84 „

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[1] In the calculation of the analyses of pyroxenes I have accepted the method followed by F. W. Clarke in R. Heber Bishop, Investigations and Studies in Jade, New York 1906, I, p. 133.

The chemical composition of the eclogite was now calculated with the following result:

	%	Mol. numb.	Mol. %	Norm	
SiO_2	48.7	812	47.6	Orthoclase	1.11
Al_2O_3	11.7	115	6.7	Albite	3.14
Cr_2O_3	0.2	1	0.1	Anorthite	30.02
Fe_2O_3	1.4	9	0.5	Σ sal =	34.27
FeO	6.8	97	5.7	Diopside	30.98
MnO	0.2	—	—	Hypersthene	18.06
MgO	16.7	417	24.4	Olivine	14.70
CaO	13.9	248	14.5	Magnetite	2.09
Na_2O	0.4	6	0.3		
K_2O	0.2	2	0.1	Σ fem =	65.83
H_2O	0.1	—			
	100.3		100.0		100.10

In the quantitative classification this eclogite belongs to the subrang palisadose, IV, 1, 2, 2, 2. In Washington's tables there are not very many analyses representing this subrang; some of them agree closely with the above figures, and among them are some of abyssal as well as of volcanic rocks. We may note an olivine-gabbro from Orange Grove, Baltimore County, Maryland, which, according to G. H. Williams[1], is composed of diallage, hypersthene, anorthitic plagioclase and olivine, the latter with reaction rims where it is in contact with feldspar. This rock thus has a nearly normative mineral composition. Other nearly identical analyses represent hornblendite, a monomineralic rock of the amphibolite facies.

The structure of this eclogite is shown in fig. 1, pl. I. The garnet, in the eclogite from Almklovdalen, occurs in the manner of rounded phenocrysts, measuring about one cm. in diameter. They are practically free from inclusions and, as H. Reusch points out, are cut by a set of cracks parallel to one other in all the individual crystals of a specimen. In other ways the eclogite shows no parallel structure, the surrounding olivine-rock, on the other hand, showing the most pronounced foliation.

The pyroxene also occurs as phenocryst-like, rounded individuals, a little smaller than the crystals of garnet. All these phenocrysts are embedded in an evenly granular millimeter-grained ground-mass composed of the same kind of pyroxene as the phenocrysts. Trifling amounts of pale green amphibole are found at the contacts between the garnet and the pyroxene, and in still smaller quantities there occur flakes of chlorite and grains of brown rutile. Apatite seems to be absent. Still an accessory mineral is pyrite that, in the form of minute hexahedra, is evenly distributed in all the thin sections studied.

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[1] U. S. G. S. A. R. 15, p. 674, 1895.

The chloromelanite-eclogite of Duen type from Vanelvsdalen, Søndmøre.

M. Irgens and Th. Hiortdahl have collected specimens of eclogite marked "Duen, Vanelvsdalen", and many later describers of the Norwegian eclogites have mentioned this occurrence. The present writer found quite similar eclogite near Duestøl in Almklovdalen (the upper Vanelvsdalen), and this may be the same locality. Eclogites, mineralogically and structurally identical with the Duen eclogite were found at several places, e. g. Almklovsaeter in Almklovdalen and near Tuen in Vanelvsdalen, and they are very frequent in this tract as erratic boulders. Thus a specimen in the collections of the museum marked "erratic boulder, Vanelvsdalen" was chosen for quantitative study because of the unaltered character of its minerals. Although it is not certain that this specimen has been derived exactly from the Duen or Duestøl occurrence, we may yet designate it as "eclogite of the Duen type".

The eclogites of the Duen type occur as lenticular inclusions in gneiss.

Of the garnet that part was taken that floated in a solution of sp.g. = 4.02 and sank in that of sp.g. = 3.97. The analysis of this deep red garnet was executed by Mr. L. Thomassen with the following result:

	$^0/_0$	Mol. number	
SiO_2	38.40	640	640
TiO_2	0.40	5	
Al_2O_3	21.01	207	218
Cr_2O_3	0.00		
Fe_2O_3	1.80	11	
FeO	25.64	356	621
MnO	0.70	10	
MgO	4.02	101	
CaO	8.61	154	
H_2O	0.15		
	100.73		

Sp. g. = 3.99

n_D = 1.7911

$RO_2 : R_2O_3 : SiO_2 = 2.85 : 1 : 2.96$

Composition: $(Fe_{57}Mn_2Mg_{16}Ca_{25})_3(Al_{95}Fe_5)_2$.

In diluting the Clerici solution the pyroxene just floated when the sp.g. was 3.38. After the removal of all that sank at this degree of dilution the solution was brought to the sp.g. 3.35, and what now sank down was purified further and used for an analysis that was made by Mr. L. Thomassen with the following result:

	0/0	Mol. number
SiO_2	54.03	900
TiO_2	0.54	6
Al_2O_3	11.54	114
Cr_2O_3	0.00	—
Fe_2O_3	5.62	34
FeO	4.09	60
MnO	0.05	—
MgO	5.13	128
CaO	11.82	211
Na_2O	6.81	110
K_2O	0.20	2
H_2O	0.29	—
	100.12	

Sp.g. = 3.365
β = 1.697 ± 0.002
$c : \gamma$ = $41^\circ \pm$.

The optical character is positive, and the axial angle is larger than in common diopside. I measured with Klein's lens $2\,E = 149^\circ$, from which $2\,V = 82^\circ\,40'$.

Dispersion of the optic axes is strong, $\rho > v$, and it is stronger in axis A than in axis B. Sections nearly perpendicular to the optic axes show abnormal lavender-blue interference colours.

S. Franchi found the dispersion in chloromelanitic pyroxenes to rise with the quantity of ferric oxide[1]. The present pyroxene, containing 5.62 0/0 Fe_2O_3, seems to confirm his conclusion.

The mineral is megascopically very dark green and, in thin sections, shows a beautiful intense green tint that would suggest the presence of chromium. The chemical test, however, proved chromium to be absent. Pleochroism is almost imperceptible: the colour for β appears to be a little deeper green than for α and γ.

The intense green colour apparently may be ascribed to the presence of the large amounts of aegirite, but the present pyroxene differs from the latter in the absence of pleochroism, probably due to the predominance of the jadeite.

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[1] S. Franchi, Sulla dispersione nei pirosseni cloromelanitici di alcuni roccie cristalline delle Alpi occidendali. Boll. Comm. geol. d'Italia. 1901, N:o 4.

The chemical composition may be calculated as follows:

	0/0	Jadeite (Na, K) Al Si_2O_6	Aegirite Na Fe Si_2O_6	Pseudojadeite (Ca, Mg) (Al, Fe)$_2$ Si_4O_{12}	Diopside (Mg, Fe, Mn) Ca Si_2O_6	Excess
SiO_2	54.03	20.64	6.24	4.32	21.60	1.23
TiO_2	0.54					0.54
Al_2O_3	11.54	8.77		2.77		
Fe_2O_3	5.62		4.16	1.46		
FeO	4.09				4.09	
MnO	0.05				0.05	
MgO	5.13			0.20	4.93	
CaO	11.82			1.72	10.10	
Na_2O	6.81	5.21	1.60			
K_2O	0.20	0.20	—			
H_2O	0.29					0.29
	100.12	34.82	12.00	10.47	40.77	2.06

Jadeite	34.82
Aegirite	12.00
Pseudojadeite	10.47
Diopside	40.77
Unaccounted for	2.06
	100.12

This pyroxene is a typical representative of the mixtures of diopside, jadeite and aegirite called *chloromelanite*. We quote, for comparison, a few analyses of chloromelanite and chloromelanitite, a rock composed chiefly of chloromelanite. I. Chloromelanite from St Marcel, Piedmont (S. L. Penfield, Am. J. Sc. 46, 292, 1893). II. Chloromelanitite from Le Sinette, Mocchie, Val de Susa, Piedmont (S. Franchi, Boll. Com. geol. d'It. 1900, n:o 2, p. 143). III. Chloromelanitite from St Marcel, Piedmont (Damour, quoted in Zs. Kr. 6, 291). IV. Chloromelanite from Vanelvsdalen.

	I	II	III	IV
SiO_2	54.39	56.85	55.82	54.03
TiO_2	—	—	—	0.54
Al_2O_3	9.93	8.42	10.95	11.54
Fe_2O_3	11.78	9.82	5.68	5.62
FeO	n.d.	1.12	n.d.	4.09
MnO	0.66	tr	—	0.05
Mn_2O_3	1.21	—	—	—
MgO	5.01	4.57	9.05	5.13
CaO	7.29	12.16	13.42	11.82
Na_2O	9.40	6.91	6.74	6.81
K_2O	0.24	0.28	—	0.20
H_2O	0.38	0.59	—	0.29
	100.29	100.72	101.66	100.12

From 58 g of ground rock was obtained 1 g iron ore and rutile which sank in a solution of sp.g. 4.13. This quantity was treated with hydrofluoric and sulphuric acids whereby the iron ore was dissolved and rutile alone was left. In the ore I found 36 % TiO_2, but no chromium. Assuming it to be ilmenite-magnetite, I calculated the following composition:

TiO_2 . . . . 36 %
FeO . . . . 41 „
Fe_2O_3 . . . . . . 23 „

That portion whose specific gravity was less than 3.35 contained apatite and a myrmekite-like intergrowth of pyroxene and plagioclase. By boiling with nitric acid, 50 % of it was dissolved and considered as apatite, seen in large amounts under the microscope. This apatite was found to contain 0.27 % Cl. Assuming that only chlorine-apatite and fluorine-apatite take part in its composition this apatite should contain nearly 95 % fluorine-apatite.

The quantitative mineral composition, or mode, arrived at by the mechanical analysis is given in the following table where, as an example of the method, the whole calculation of the bulk composition of the rock from the mode and the analyses of the minerals is quoted.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	F	Cl
Garnet . . . . . 55.10 %	20.99	11.51	0.98	14.02	0.38	2.20	4.71	—	—	0.23	—	—	—
Pyroxene[1] . 38.05 „	20.51	4.38	2.05	1.62	0.02	1.95	4.49	2.59	0.08	0.20	—	—	—
Apatite . . . . 5.80 „	—	—	—	—	—	—	3.16	—	—	—	2.41	0.21	0.02
Ilmenite-magnetite 1.42 „	—	—	0.33	0.58	—	—	—	—	—	0.51	—	—	—
Rutile . . . . . 0.31 „	—	—	—	—	—	—	—	—	—	0.31	—	—	—
100.68 %	41.50	15.89	3.36	16.22	0.40	4.15	12.36	2.59	0.08	1.25	2.41	0.21	0.02

Sum 10

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[1] Inclusive 5.7 % pyroxene-plagioclase-myrmekite.

Or, tabulated in the usual way:

	0/0	Mol. numb.	Mol. 0/0	Norm	
SiO_2	41.5	692	47.0	Orthoclase	0.56
Al_2O_3	15.9	156	10.4	Albite	19.39
Cr_2O_3	0.0	—	—	Anorthite	31.41
Fe_2O_3	3.4	21		Nephelite	1.42
FeO	16.2	225	18.1	Σ sal	52.78
MnO	0.4	6		Diopside	12.11
MgO	4.2	104	6.9	Olivine	22.71
CaO	12.4	221	14.7	Magnetite	4.87
Na_2O	2.6	42	2.8	Ilmenite	2.28
K_2O	0.1	1	0.1	Apatite	5.71
TiO_2	1.2	15	—		
P_2O_5	2.4	17	—	Σ fem	47.68
F	0.2	6	—		
Cl	0.02	—	—		
H_2O	0.2	—	—		
	100.7		100.0		100.46

Sp.g. = 3.61 (t = 12°).

Auvergnose, III, 5, 4, 3.

Disregarding the exceptionally high percentage of apatite this chloromelanite-eclogite shows a typical gabbroic composition, though the ferrous oxide is rarely found in such a large proportion to the magnesia. Yet such rocks occasionally occur also in large areas with a great persistency of the composition. We may mention the geologically well defined series of so-called olivine-diabases in Satakunta in Finland and Nordingrå and Åsby in Sweden[1], the analyses of which we meet when seeking those nearly identical to the above figures. These rocks are almost normative in their mineral composition, belonging to the gabbro facies. In the amphibolite facies such a composition would probably give rise to a spinel-bearing amphibolite or perhaps an olivine-amphibolite.

The specimen of chloromelanite-eclogite studied was exceptionally un altered. The grains of pyroxene, however, are surrounded by zones of myrmekite-like intergrowth of pyroxene and plagioclase, 5.7 per cent of the whole rock. It shows sharp boundaries towards the unaltered pyroxene. A discussion of this kind of alteration follows on later pages. It is very apparent in this case that the alteration means a recrystallization of diopsidic pyroxene and plagioclase instead of the original pyroxene rich in jadeite and lime-pseudojadeite. Amphibolitization, or feldspar-uralitization, has not taken place; the rock contains but minute traces of dark green hornblende apart from the plagioclase.

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[1] J. M. Sobral, Contributions to the geology of the Nordingrå area, Bull. Geol. Inst. University of Upsala, XII, 1913.

The structure (fig. 2, pl. I) is somewhat porphyritic, the rounded crystals of garnet, from 2 to 5 mm in diameter, appearing as phenocrysts. The chloromelanite forms a medium-grained ground-mass where the grains show an indistinct parallel arrangement.

The Eclogite from Lyngenes, Sørpol, Selje, Nordfjord.

This eclogite belongs to a fine-grained and distinctly foliated type. The specimens kept in the collections of the Geological Museum in Christiania have been collected by H. Reusch in 1886. No further details about its mode of occurrence are known but that it is an occurrence in the gneiss. During my excursions I met with similar rocks at many places as inclusions in gneiss.

A bulk analysis of this eclogite was executed by Mr. L. Thomassen with the following result.

	0/0	Mol. numb.	Mol. 0/0	Norm	
SiO_2	45.33	755	45.9	Orthoclase	1.11
Al_2O_3	13.06	128	7.6	Albite	6.81
Cr_2O_3	tr	—		Anorthite	31.69
Fe_2O_3	1.58	10		Σ sal	39.61
FeO	12.73	176	11.8	Diopside	4.94
MnO	0.22	3		Hypersthene	24.29
MgO	17.28	432	25.7	Olivine	26.49
CaO	7.57	136	8.1	Magnetite	2.32
Na_2O	0.79	13	0.8	Ilmenite	2.58
K_2O	0.16	2	0.1		
TiO_2	1.35	17	—	Σ fem	60.62
P_2O_5	0.19				
H_2O	0.22				
	100.48		100.0		100.23

Sp.g. = 3.570 (t = 12°).

Auvergnose, III, 5, 4, 3, near wehrlose.

In the gabbro facies such a composition would result in an olivine-norite, poor in feldspar. In the amphibolite-facies the rock would crystallize without feldspar, as a hornblende-peridotite. Of both kinds of rocks there are actual examples with sufficient approximation of the composition to the above figures.

Our eclogite is actually composed of garnet, clinopyroxene, pale green hornblende, olivine, black iron ore, rutile and a little apatite.

The garnet has

$$n_D = 1.7585.$$

As the rock-analysis indicates that this garnet, like all the eclogite garnets from Søndmøre analyzed, must be low in lime, we may safely assume its composition to be between those of the garnet from Almklovdalen (n = 1.7498) and from Silden in Selje (n = 1.7660), and calculate it graphically from their refractive indices. We obtain the following percentage figures: 41.1 SiO_2, 22.4 Al_2O_3, 1.7 Fe_2O_3, 16.1 FeO, 0.4 MnO, 14.1 MgO and 4.9 CaO, conforming to the atomic formula $(Fe_{34}Mg_{53}Ca_{13})$. From our diagram (fig. 1, p. 9) would result $(Fe_{34}Mg_{48}Ca_{18})$.

The amount of garnet may be estimated at 55 per cent. The compounds entering into it having been subtracted from the bulk analysis, the rest shows (Mg,Fe)O in large excess over the lime in the diopside ratio, and little alumina. The largest part of the remainder consists of clinopyroxene in long prismatic anhedral crystals. This pyroxene probably contains greater part of the alkalies in the rock, but it is not so rich in alkali as the pyroxene in the eclogite of the Duen type. The pale green hornblende occurs much in the same manner as the pyroxene, in the form of long prisms.

The olivine occurs as more rounded individuals which are always intergrown with black iron ore. The intergrowth has some resemblance to myrmekite, but it is present in almost all the olivine. The axial angle in the latter is almost 90° indicating a mixture with about 10 per cent fayalite. The olivine is always accompanied by a bright brown iddingsite-like mineral.

Iron ore, probably ilmenite, also occurs as larger anhedral crystals.

The foliated structure of this eclogite is due to a parallel arrangement of the pyroxene and hornblende prisms and the elongated groups of garnet crystals (fig. 3 pl. I).

The eclogite in Lyngenes, though occurring in gneiss, shows more resemblance to the eclogite in Almklovdalen which is in olivine-rock than to any of the other occurrences in gneiss investigated. Chromic oxide, however, is only present in traces, and the alkalies are somewhat more abundant.

The Eclogite from Silden, Nordfjord.

A specimen of eclogite from a lens in gneiss, 1 m long, occurring on the island Silden in Selje and collected by H. Reusch, was subjected to a quantitative investigation.

By separation with Clerici's solution there was obtained:

Pyroxene	57.7 $^0/_0$
Garnet	34.1 „
Quartz Mica	7.9 „
Rutile	0.3 „
	100.0 $^0/_0$

Sp.g. = 3.415 (t = 13°).

A calculation from the specific volumes of the minerals in this rock gave the specific gravity of the rock as 3.43, in close agreement with direct observation.

The garnet was analyzed by the writer with the following result:

	$^0/_0$	Mol. numb.	
SiO_2	40.30	672	672
TiO_2	tr[1]	—	
Al_2O_3	21.86	215	229
Fe_2O_3	2.16	14	
FeO	19.08	265	650
MnO	0.69	10	
MgO	11.28	282	
CaO	5.22	93	
	100.59		

Sp. g. = 3.882 (t = 12°).

n_D = 1.7660.

$RO : R_2O_3 : SiO_2$ = 2.83 : 1 : 2.93.

Composition: $(Fe_{40}Mn_2Mg_{43}Ca_{15})_3(Al_{94}Fe_6)$.

The following is the analysis of the pyroxene made by the writer:

	$^0/_0$	Mol. numb.
SiO_2	55.56	926
TiO_2	0.15	1
Al_2O_3	7.17	70
Fe_2O_3	2.82	18
FeO	2.06	29
MnO	0.05	—
MgO	11.32	283
CaO	16.85	301
Na_2O	3.92	63
K_2O	0.57	6
H_2O	0.08	—
	100.55	

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[1] Less than 0.10 $^0/_0$.

Sp.g. = 3.330.
β = 1.683 = 0.002.
$\gamma - \alpha$ = 0.024 in max.
2V = 67° appr.
Dispersion weak, $\rho > v$.
c : γ = 42° appr.

Colour in thin section is faintly greenish, non-pleochroic.

The composition of this pyroxene is:

	$^0/_0$	Jadeite (Na, K) (Al, Fe) Si_2O_6	Pseudojadeite (Ca, Mg) (Al, Fe)$_2$ Si_4O_{12}	Diopside Ca (Mg, Fe) Si_2O_6	Excess
SiO_2	55.56	16.56	4.56	35.58	— 1.20
TiO_2	0.15				0.15
Al_2O_3	7.17	5.71	1.46		
Fe_2O_3	2.82	2.08	0.80		
FeO + MnO	2.11		0.07	2.04	
MgO	11.32		0.36	10.96	
CaO	16.85		0.50	16.35	
Na_2O	3.92	3.92			
K_2O	0.57	0.57			
H_2O	0.08				0.08
	100.55	28.84	7.75	64.93	—0.97

Diopside	64.93
Jadeite	28.84
Pseudojadeite	7.75
Unaccounted for	—0.97
	100.55

The rutile, as usual, is the most prominent minor constituent, appearing as irregular or rounded grains of dark brown colour.

The quartz and the mica were not separated, and their percentages, very variable even in the small rock-body described, were roughly estimated at 5.9 $^0/_0$ quartz and 2 $^0/_0$ mica. The bulk composition of the rock was now calculated from the mode and the above analyses of garnet and pyroxene. For the mica, which is moderately pleochroic, α = colourless $< \beta = \gamma$ = brownish yellow, 2E = 22°, was used the analysis of biotite from quartz-monzonite, Walkerville Station, Butte, Mont (Quant. Classific. table XIV, analysis c). The following result was arrived at:

	%	Mol. numb.	Mol. %	Norm	
SiO_2	52.4	873	52.8	Orthoclase	2.78
Al_2O_3	11.9	117	7.1	Albite	19.39
Fe_2O_3	2.4	15		Anorthite	20.85
FeO	8.0	111	8.7	Σ sal	43.02
MnO	0.2	3		Diopside	29.17
MgO	10.6	265	16.0	Hypersthene	20.84
CaO	11.5	205	12.4	Olivine	2.90
Na_2O	2.3	37	2.2	Magnetite	3.48
K_2O	0.5	5	0.3	Ilmenite	0.76
TiO_2	0.4	5	0.3	Σ fem	57.15
H_2O	0.1	—			
	100.3		99.8		100.17

Ornose, III, 5, 3, 5.

A similar composition is common in basalts as well as in gabbroic rocks, the latter always containing orthopyroxene, if they do not belong to the amphibolite-facies, in which case they may consist almost exclusively of hornblende. A basalt from the Hawaiian islands having nearly identical bulk composition is said to contain phenocrysts of olivine.

In the Silden eclogite all the minerals are unaltered, excepting narrow zones around the pyroxene crystals which are turbid from incipient separation of diopside-plagioclase-myrmekite. These zones are so thin that they rather appear as thick boundary-lines drawn with a coarse pencil.

The structure is shown in fig. 4, pl. I. Parallel arrangement of the minerals is not very pronounced. The rutile is found equally enclosed in all the minerals, the garnet shows crystalline forms towards the pyroxene and quartz, while the pyroxene is always irregular.

The Eclogite from Saltkjael, Selje, Nordfjord.

In the collections of the Geological Museum in Christiania there exists a specimen collected by H. Reusch and marked "from a 3 foot thick layer in gneiss, Saltkjael, Selje". The rock is aphanitic, and at first sight I thought it to be some hornfels. Microscopic observation revealed garnet and clinopyroxene as the main minerals, besides a little pale brown mica. The average pyroxene grain is 0.15 mm in diameter, while the rounded grains of garnet attain 0.3 mm.

This rock attracted my interest because its pyroxene showed a rather striking optical characteristic, in having an exceptionally low birefringence: in a section of 0.02 mm thickness the highest interference colour is pale yellow of the first order, as in the orthopyroxenes. Knowing from Laura Hezner's description[1] an eclogite-rock from Schaffis, Switzerland, whose pyroxene shares this character and contains much alumina and lime, I decided to separate the pyroxene from the Saltkjael eclogite for analysis.

The minerals, however, almost defied separation. Three separations were necessary, and the sample obtained, floating at sp. g. 3.320 and sinking at sp. g. = 3.356 and consisting of approximately pure pyroxene, was but 0.4 g in weight. On this amount an analysis was carried out by Mr. L. Thomassen:

	%	Mol. numb.
SiO_2	48.61	810
Al_2O_3	14.60	143
FeO	10.46	145
MgO	9.66	241
CaO	13.32	238
Na_2O	2.07	34
K_2O	0.42	4
	99.14	

Sp. g. 3.34

$\beta = 1.685 \pm 0.003.$

$\gamma - \alpha = 0.018 \pm 0.001.$

$2V\gamma = 60^\circ$ appr.

No noticeable dispersion of the optic axes.

Colourless in thin section.

The state of oxidation of the iron was not determined. The optical properties, however, make it probable that only ferrous oxide is present.

This analysis may be calculated in the following way:

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[1] Laura Hezner, Ueber einige in schweizerischen Pfahlbauten gefundene Steinwerkzeuge, N. J. Min. etc. B.-B. XX, 1905 p. 141.

	0/0	Jadeite (Na, K) Al Si_2 O_6	Tschermak's silicate (Mg, Fe) Al SiO_6	Diopside Ca (Fe, Mg) Si_2O_6	Hypersthene (Mg, Fe) SiO_3	Excess
SiO_2	48.61	9.12	6.30	28.56	2.58	2.05
Al_2O_3	14.60	3.87	10.73			
FeO	10.46		2.88	6.34	1.22	
MgO	9.66		2.60	6.00	1.06	
CaO	13.32			13.32		
Na_2O	2.07	2.07				
K_2O	0.42	0.42				
	99.14	15.48	22.51	54.22	4.86	2.05

Diopside	54.22
Tschermak's silicate	22.51
Jadeite	15.48
Hypersthene	4.86
Unaccounted for	2.05
	99.12

For comparison we quote the analysis of a "jadeitic" stone axe from Schaffis, Biel Lake, Switzerland (I), made by Laura Hezner[1] and of "jadeite" from an erratic boulder, La Téne, Switzerland (II) made by A. Frenzel[2]. Both are bulk-analyses of rocks, but they consist chiefly of pyroxene and contain only accessory garnet and rutile. III is the analysis of pyroxene from Saftkjael.

	I	II	III
SiO_2	48.45	50.30	48.61
TiO_2	0.19	—	—
Al_2O_3	25.29	25.68	14.60
FeO	2.59	2.79	10.46
MgO	6.33	4.45	9.66
CaO	10.86	11.00	13.32
Na_2O	4.67	6.30	2.07
K_2O	1.00	—	0.42
H_2O	0.58	—	—
	99.96	100.52	99.14

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[1] L. Hezner, N. Jb. f. Min. etc. B.-B. XX, p. 141.

[2] A. B. Meyer, Antiqua 1884, quot. N. J. f. Min. etc. 1885, II, 7.

The pyroxene from Saltkjael presents an example of aluminous eclogite pyroxenes in which the proportion of alumina is largely excessive over the alkalies. Its excessive alumina is less than in the Swiss examples, and it differs from these in the prevalence of ferromagnesia.

The clinopyroxene is the most abundant constituent of the aphanitic eclogite from Saltkjael. Garnet is the next in quantity, and pale brown biotite is an accessory. Chloritic substances occuring between the rounded grains of pyroxene and garnet represent later products.

The Eclogite-hornblendegabbro of Romsdalshorn.

The occurrence of eclogite-hornblendegabbro at the foot of Romsdalshorn has been described by Th. Kjerulf[1]. The main part of that mountain consists of granitic gneiss in which is enclosed a sheet-like mass of the eclogite-gabbro, by Kjerulf named eclogite, measuring 70 feet in thickness. Other thinner sheet-like masses consist of amphibolite. All these are stratified parallel to the foliation of the gneiss.

I propose to call this rock eclogite-hornblendegabbro, because it contains both the minerals of an eclogite and those of a hornblende-gabbro. An analysis of the rock, executed by the writer, gave the following results:

	%	Mol. numb.	Mol. %	Norm	
SiO_2	44.61	743	48.82	Orthoclase	11.12
Al_2O_3	15.68	154	10.12	Albite	17.55
Fe_2O_3	1.81	11		Anorthite	25.02
FeO	15.88	221	16.23	Nephelite	2.98
MnO	0.28	4		Σ sal	56.67
MgO	5.70	142	9.32	Diopside	9.81
CaO	7.37	132	8.67	Olivine	24.01
Na_2O	2.70	44	2.89	Magnetite	2.55
K_2O	1.89	20	1.31	Ilmenite	6.08
TiO_2	3.21	40	2.62	Σ fem	42.45
P_2O_5	n.d.				
H_2O	0.52				
	99.65		99.98		99.12

Camptonose, III, 5, 3, 4.

Sp. g. = 3.20 (t = 12°).

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[1] Th. Kjerulf, Udsigt over det Sydlige Norges Geologi, 1879, pag. 222.

The eclogite-gabbro of Romsdalshorn has a composition not very usual in gabbroid rocks, being characterized by the prevalence of ferrous iron over magnesia. In Washington's Tables we find, however, a number of nearly identical analyses. Most of them are of olivine-bearing rocks, as e. g. a troctolite from Anabohitry, Madagascar, described by A. Lacroix[1]. But some are devoid of olivine, e. g. many gabbros and norites from the Adirondack Region, described by J. F. Kemp[2]. Their minerals are labradorite, hypersthene, garnets, green augite, brown hornblende, biotite, magnetite, apatite. It is noteworthy, that these rocks also contain garnet, being in them of a posterior origin. This mineral here apparently takes the place of the olivine in so far as it contains orthosilicates. As we will set forth later, the high proportion of ferrous oxide is favourable for the growth of late garnet as well as for the preservation of primary garnet, which in all such cases belongs to the almandite series.

The mineralogical composition of the eclogite-gabbro being very complicated, no mode can be calculated. The garnet and the clinopyroxene apparently are the most abundant constituents, after which follow plagioclase, hornblende, biotite and ilmenite. Apatite and rutile are minor constituents.

The garnet, separated by means of Clerici's solution, was analyzed by the writer with the following result:

	%	Mol. numb.	
SiO_2	38.57	643	643
TiO_2	0.05	—	
Al_2O_3	19.04	186	209
Cr_2O_3	0.00		
Fe_2O_3	3.60	23	
FeO	27.43	381	625
MnO	0.62	8	
MgO	4.99	125	
CaO	6.21	111	
	100.51		

Sp. g. = 3.97.

$n_D = 1.7965$.

$RO : R_2O_3 : SiO_2 = 2.99 : 1 : 3.08$.

Composition: $(Fe_{61}Mn_1Mg_{20}Ca_{18})_3(Al_{89}Fe_{11})_2$.

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[1] A. Lacroix, Bull. Soc. France Min. 1908, 323.

[2] J. F. Kemp, U. S. G. S. Bull. n:o 168, 1900, 37.

The garnet is brownish red in colour. It contains a few inclusions, some of which are rounded and may be quartz, whilst other are small prisms with high birefringence, probably rutile.

The pyroxene is pale green of various intensity and with no noticeable pleochroism. $2V\gamma$ about 50°. This mineral shows a myrmekite-like intergrowth with plagioclase (fig. 5, pl. I).

The hornblende is chiefly found as groups of small crystal grains around the pyroxene. Its colours for β and γ are dark brown and greenish brown with very strong absorption, and for α brownish yellow. Locally this brown hornblende is seen to grade over into a green variety. The biotite also is dark brown. Like the former it is mainly found enclosed in the plagioclase, whose lamellae, of the albite twin type, in sections $\perp$ PM show $\alpha' : M = 8^\circ$, corresponding to Ab_{73}, but many crystals show a zonal structure, their central parts being more anorthitic.

The plagioclase, especially the more albitic plagioclase which forms the largest part of it, is present in the form of large xenomorphic individuals which envelope all the other mineral grains. Of these the garnet, pyroxene, apatite and rutile occur more in the form of independent crystals, though very rounded and the pyroxene often ragged. The biotite and hornblende and also the ilmenite are intimately associated with the plagioclase as small enclosed grains.

Probably the garnet and pyroxene were the first minerals to crystallize out in this rock, and it seems that the hornblende and plagioclase were formed later at the expense of the former. This change apparently took place at the last stage of consolidation.

The evident resorption of the earliest minerals, however, was hardly a phase of a normal process of crystallization, but rather due to changes in the attendant physical conditions during that process. Or perhaps there was a re-fusion of a true eclogite already crystallized, and re-consolidation of the hornblende-plagioclase mass now appearing as a mesostasis.

We arrive at the conclusion that the eclogite-hornblende-gabbro of Romsdalshorn contains two sets of minerals originated at different stages of the rock development and under different conditions. The earlier one belongs to the eclogite facies while the later represents the typical hornblende-gabbro facies.

Structural Types of Eclogite.

The specimens on which the above quantitative investigations were carried out were selected mainly as representatives of different structural types. I did not then know, what was found later, on closer acquaintance, that the chemical composition varies quite independently of the structure, which is a function of the physical conditions during and, in part, after the consolidation. It was much by accident that the examples studied nevertheless happened to comprise the most important and some of the most extreme chemical types as well.

A description of the primary structures of the eclogite can therefore be given most briefly by referring to the examples subjected to quantitative investigation.

1. *The Rødhaugen type* occurring only in the eclogites forming bands in the olivine-rock. Coarse-grained. Either garnet or pyroxene, or both, show a tendency towards phenocryst-like development.

2. *The Duen type.* Non-foliated or indistinctly foliated, porphyritic structure with rounded phenocrysts of garnet in a fine-grained or medium-grained ground-mass of pyroxene, occasionally with amphibole. The example analyzed was a chloromelanite-eclogite rich in iron. In both these characters, i. e. the percentage of jadeite in the clinopyroxene and almandite in the garnet, the eclogites of similar appearance, however, may be greatly variable.

This type is represented in all the occurrences in Almklovdalen not enclosed in the olivine-rock, but there are many other types as well. Near Duestøl and Almklovsaeter the rock is much banded and many bands consist of margarite- and labradorite-bearing rocks[1], transitional into the labradorite-rock.

Eclogites of the Duen type are very common as erratic boulders in Almklovdalen and Vanelvsdalen. The most beautiful and typical specimens have been collected from these. This only proves that there are many occurrences so far not yet found exposed. In fact, at every little trip on the mountains near Almklovdalen I found several occurrences of eclogite not recorded formerly.

The same type also is represented in the specimens from almost all the occurrences in Nordfjord and Møre so far known.

In the old specimens marked "Duen, Vanelvsdalen" the garnet shows a zonal structure. The central parts are more dark red in colour and have notably higher refringence, thus being richer in iron than the border-zones.

3. *The Lyngenes type.* Extremely foliated, fine- and even-grained. The pyroxene, with amphibole, is present in the form of long prisms and the garnet as small grains arranged in rows parallel to the foliation. Often very distinctly banded, with alternating laminae rich in pyroxene and garnet respectively.

Specimens of the same type as the analyzed rock from Lyngenes near Sørpol in Selje have been collected from Langeland near Hellesylt, Sunelven and from Ullahammer on the island Haram. I found similar rocks near Bryggen in Nordfjord closely associated with the other types of eclogite.

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[1] Margarite as a constituent of eclogites was first observed by me in a specimen from Hellebust in Almklovdalen, collected by Prof. C. F. Kolderup and kept in Bergens Museum.

This is the protoclastic structural modification of eclogite, while the non-foliated porphyritic Duen type represents that form of igneous eclogite which solidified under the most quiet conditions.

4. *The Silden type.* Distinctly foliated, almost even-grained, medium-grained, the pyroxene present as short prisms, the garnet as lenticular aggregates. Often banded. This type is transitional between 1 and 2.

To this type belong some very beautiful occurrences on the islands Silden and Barmen and near Listo in Selje and near Bryggen in Nordfjord.

5. *The Saltkjael type.* Aphanitic. I have found mylonitized eclogite resembling the aphanitic rock from Saltkjael in Selje, and it is not quite certain whether it is a posterior mylonitic or a primary protoclastic structure. The rock occurs as a narrow band in the gneiss. Other similar examples have not been met with.

6. *The Romsdalshorn type.* Non-foliated, even-grained and medium-grained. Characterized by a double set of minerals: those of a hornblende-gabbro besides the eclogite-constituents. Represented, besides in the type-locality, in several occurrences near Romsdalsfjord, as Gryten and Runeberget.

The evidence of this peculiar structure will be again discussed in the chapter on the change of the facies.

Besides these types, examples of which were studied quantitatively, we may add short descriptions of the following primary types.

7. *Amphibole-eclogite of the Gangeskar type.* Mainly composed of garnet with coarse long-prismatic amphibole.

A specimen from the "cape west of Gangeskar" in Selje is composed of clinoamphibole, colourless clinopyroxene and red garnet with brown rutile and colourless zircon as minor constituents

The amphibole is megascopically dark green, in thin sections almost colourless, and optically negative with large axial angle; $c : \gamma = 27^\circ$. It is present as anhedral crystals of an average size of about $0.5 \times 1 \times 2$ cm. This light-coloured amphibole probably belongs to the tremolite-actinolite series. It is what, in the eclogite-literature, has been formerly called smaragdite.

All the other minerals are enclosed in this amphibole, the garnet and pyroxene as irregular grains of resorbed appearance, but the rutile and zircon mostly as microlitic euhedral crystals. The pyroxene has the common omphacite characters and $2V\gamma$ about 60°. The Gangeskar specimens are almost non-foliated, while most other occurrences consist of foliated varieties.

This is a common rock type, though often still much coarser in grain. I have observed it near Aaland in Bryggen, in a banded occurrence of eclogite whose other bands consist of the Lyngenes and Duen types and in part of garnet- and pyroxene-rock.

On Aasnaes near Bryggen it is associated with a finely banded eclogite and at another point it forms an 8 meters thick lens in which the garnet is somewhat concentrated in certain bands. The garnets, in both the last-named occurrences, are rounded and of larger size than they are in the common pyroxene-eclogite. When embedded in the large crystals of amphibole, they are surrounded by thin zones of deeper green hornblende forming the continuation of the colourless amphibole. Zoisite is present as large prisms.

The eclogites of Duen type in Vanelvsdalen commonly contain irregular patches or nodules of such amphibole-eclogite.

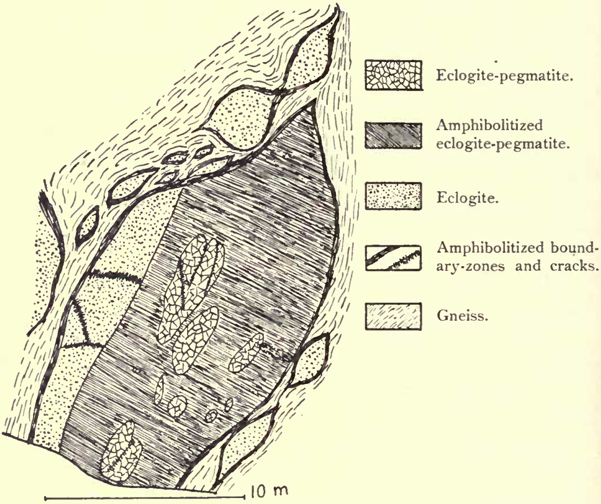
Eclogite-pegmatite.
Amphibolitized eclogite-pegmatite.
Eclogite.
Amphibolitized boundary-zones and cracks.
Gneiss.
10 m

Fig. 4. Eclogite-pegmatite in gneiss. Grytingvaag, Selje.

Many eclogites contain similar pale-green amphibole (smaragdite) as large crystals besides dominant pyroxenes, and may be understood to be transitional between the true pyroxene-eclogites and the amphibole-eclogites. In such rocks there is nowhere any proof of posterior alteration of the pyroxenes into amphibole. It seems more probable that the amphibole has originated at the later stage of the magmatic crystallization.

In the Gangeskar eclogite the pyroxene and garnet both present themselves as relics, and the development of the rock probably was somewhat as follows: Garnet and ortho- and clinopyroxene had crystallized out from the magma in the usual way, but the consolidation did not end with these phases, probably because mineralizers were present in larger amounts than usually and residual magma was still present, when the temperature had sunk below the stability limit of the eclogite facies. The clinoamphibole then began to crystallize and, at the same time, resorption of the pyroxene and, though in smaller degree, of garnet set in.

The amphibole-eclogite differs from the eclogite-gabbro of the Romsdalshorn type as well as from partly amphibolitized eclogites in the absence of plagioclase, and in the tremolitic character of the amphibole. Therefore, if the amphibole-eclogite actually originated by magmatic resorption and recrystallization in the manner just outlined, we must assume that the amphibole was formed mainly at the expense of pyroxenes, diopside and enstatite, while the garnet remained more intact. This conforms to the actual structures, the large size and sometimes euhedral development of the garnet, and the poor development of the green kelyphite zones.

Thus this coarse-grained amphibole-eclogite presents itself as a kind of eclogite-pegmatite, and is probably related to the following type of pegmatitic development in the true eclogite facies.

8. *Eclogite-pegmatite of the Gryting type.* At Grytingvaag near the church of Selje I met with a lens of extremely coarse-grained eclogite-pegmatite (fig. 4). But small remains of it have been preserved in the original form, and the main part has been amphibolitized in such a way that the primary forms and structures have been preserved in the finest details as pseudomorphs.

The unaltered rock is mainly composed of enstatite, diopside and garnet. The enstatite and garnet may be found as crystals up to 5 centimeters in diameter or more; the diopside is somewhat finer in grain. Certain schliers of the rock still contain much coarsely crystalline carbonate and pale brown mica in large scales; in such portions also occur large prisms of pale green tremolitic amphibole.

The diopside is light emerald-green;

$$\beta = 1.680 \pm 0.002.$$

In the enstatite which is pale brown in colour were determined:

$$\beta = 1.670 \pm 0.002; \ \gamma = 1.675 \pm 0.002.$$

The garnet is brownish red;

$$n > 1.74.$$

On the one side of this eclogite-pegmatite, in the same lens, occurs an ordinary fine-grained eclogite of the Duen type. It is very rich in pyrites and has a dark green pyroxene (chloromelanite?).

By amphibolitization the enstatite at first has been converted into an asbestus-like anthophyllite. At a later stage the diopside has been uralitized and the garnet pseudomorphosed into dark amphibolitic nodules in which the minerals can not be distinguished by the naked eye.

This inclusion seems to have been detached from some larger body of eclogite intersected by primary pegmatitic dikes, one of which, together with a portion of its country-rock, has been enclosed in the gneiss.

The surrounding gneiss embraces numerous lenses of the usual fine-grained or medium-grained eclogite and is itself, in places, almandite-bearing.

There is hardly any doubt of this coarse-grained and unequal rock being analogous to true pegmatites and, on the other hand, to the amphibole-eclogites described above. In the present case the crystallization had taken place within the temperature and pressure limits of the eclogite facies proper, but the occurrence of the amphibole in the most pegmatite-like portions proves that it was not far from the lower limit of this facies.

An occurrence of a somewhat similar, pegmatite-like eclogite was described by G. Tschermak from Karstätten and Gurhof near Aggsbach in Lower Austria[1], where eclogite is associated with olivine-rock and serpentine in granulite. The eclogite contains: "faustgrosse Stücke von Granat, daran zollgrosse Omphazit- und Smaragditkörner und grosse Körner von Magnetit".

Mineralogical Varieties of Eclogite.

The typical minerals of the eclogites present in all the structural varieties are eclogite-garnet and eclogite-clinopyroxene, the specific distinctive characters of which have been discussed in "Mineral Facies", pages 171—174. Typical minor constituents are rutile and apatite, invariably present, and ilmenite and pyrite, very common.

Eclogites exclusively composed of these type-minerals have been found developed in the structural varieties 1, 2, 3 and 4.

Besides these typical constituents the eclogites frequently contain amphiboles of the tremolite-actinolite-hornblende series, biotite, quartz and plagioclase. We already touched on the problem of the rôle of the amphiboles in the amphibole-eclogites. We found proofs in their structures indicating that the amphiboles are not congenetic with the other minerals, although they may be primary minerals in the usual sense, having probably crystallized out from the magma. Yet they have originated at the expense of earlier minerals and under other conditions than the latter.

In the eclogite-gabbro of the Romsdalshorn type the combination hornblende-plagioclase plays very much the same rôle as the light-coloured amphibole in the former case.

Crystallization of amphiboles and amphibole-plagioclase mixtures may also have taken place in a metamorphic way, by amphibolitization which we shall find to be a phenomenon of universal occurrence. The rock-varieties thus developed are true alteration types whose existence depends upon posterior changes.

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[1] G. Tschermak, Beobachtungen über die Verbreitung des Olivins in Felsarten. Sitz-Ber. Wiener Ak. Wiss. 1867, 56, I, 276.

The amphiboles are regarded as not belonging to the eclogite facies.

Concerning the biotite and quartz we have no such structural evidence to decide whether they are congenetic with the pyroxene and garnet or not. It may be that they are truly congenetic.

Occasionally eclogites may contain enstatite or olivine. Both these minerals doubtless belong to the eclogite facies and their occurrence depends on defined proportions of the chemical components present.

Both olivine and enstatite, or one of them at a time, may occur in the band-shaped segregations in the olivine-rock.

In the eclogite enclosed in gneiss, olivine was observed only in the specimens from Lyngenes in Selje.

Enstatite was found in the eclogite-pegmatite at Grytingvaag in Selje and, moreover, in specimens of eclogite from Saetre on the island Hareid and from the island Sulø near Aalesund. This pyroxene shows an axial angle of almost 90°. Its crystals are surrounded by zones of dusty opaque products of alteration (fig. 6, pl. I), a good diagnostic of the orthopyroxene in eclogites. In the rock from Hareid were still observed euhedral pseudomorphic crystals of rhombic habit and lamellar structure, probably pseudomorphs after olivine

Cyanite, one of the most typical minerals of the eclogite facies, has not been met with in the eclogites of Norway. Its absence may be ascribed to the chemical composition which, in these rocks, is characteristically poor in alumina; it occurs only when alumina is present in excess of that proportion which may possibly enter into the combination of the pyroxene and garnet present (cf. Mineral Facies, p. 175).

In a certain sense the margarite, occurring in some varieties of the eclogite, may be regarded as taking the place of the cyanite, although it, being a hydrated mineral and occurring only in types showing much evidence of alteration, does not belong to the facies.

Among the posterior products commonly found in the eclogite we may mention hornblende, plagioclase, epidote and zoisite, chlorite and talc.

The Eclogite in the Olivine-Rock.

Mode of occurrence and general characters.

The first note on the eclogites among the olivine-rocks in Norway was given by H. Reusch. In his first publication on the rocks of Søndmøre and Nordfjord[1] he called the rock a garnet-olivine-rock. He writes as follows (in translation):

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[1] Loc. cit. (Forhandl. Vid. Selsk. 1877, p. 12).

"On Rødhaugen and near Lien there occur, in the compact variety of olivine-rock, a few dikes or layers, some two feet thick, of a rock of extraordinary beauty, a garnet-olivine-rock."

In the later publication of H. Reusch[1] this rock is named olivine-bearing eclogite and is said to be composed of red garnet and light green omphacite with which are associated olivine, in part in the state of incipient serpentinization, a brownish green hornblende and a little rutile.

The specimen of eclogite from Almklovdalen subjected to quantitative investigation did not contain olivine.

Besides these occurrences in Almklovdalen but one of eclogite in olivine-rock, near Tafjord in the parish of Nordalen, Søndmøre, is known. J. H. L. Vogt[2] gives the following description of it (in translation):

"On Kalskaret — the passage between Tafjord and Herdalen, several masses of olivine-rock occur". — —

"In several lenses one finds certain zones of garnet-olivine-rock — —. This is the most beautiful and finely coloured rock that I have seen, especially in weathered blocks where the red garnet and the green olivine are embedded together in the yellow weathered olivine-rock. I interpret these lenses as differentiated bands in the olivine-rock, especially as, in the garnet-olivine-rock itself, there is a steady variation of different laminae, some more coarsely grained, others richer in garnet and others richer in olivine and still others consisting of the common olivine-rock. And all these various alternating laminae which mostly grade into one another without sharp boundaries, are parallel to the jointing and foliation of the olivine-rock as well as to the elongation of the lenses and the body of olivine-rock itself".

I had two specimens of the Tafjord eclogite for study, one marked "Kalskaret, Tafjord" and another "Kjødhallen, Schweigaardsbro, Tafjord". Both are perfectly unaltered and bear much resemblance to the Almklov eclogite analyzed. They are free from olivine.

The most striking structural feature of the Tafjord eclogite is the mechanical deformation of its pyroxene. What has not been granulated shows a strong undulatory extinction and bending.

The specific gravity of the rock from Kalskaret was found to be 3.45, while that of the Almklov eclogite was 3.51.

I have myself undertaken field-studies on the occurrences in Almklovdalen. Those on Rødhaugen near Hellebust, described by Reusch, show little variation and have been more or less altered into the greenschist facies, while the rocks between the farm Lien and the little lake Helgehornsvand are very varied and many of them show such fascinating colours that one feels tempted to describe them from the artistic rather than from the petrological point of view. Still a few garnet-bearing nodules were observed in a smaller occurrence of olivine-rock at another locality named Rødhaugen, near Duestøl, and erratic boulders of eclogite etc., probably derived from the olivine-rock mass southeast of Duestøl, were found near the same farm.

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[1] Loc. cit. (Forhandl. Vid. Selsk. 1883, p. 14).

[2] Loc. cit. (Nyt Mag. Naturvidensk. 27, 1883, p. 128).

The band-formed masses, though small in size, are exceedingly variable in composition. Besides some of eclogite there are also almost monomineralic nodules consisting either of garnet or diopside, and all the possible bi-, tri- and tetramineralic associations of olivine, garnet, diopside and enstatite.

Diopside-garnet-rock or eclogite is perhaps most common. The inclusions have sharp boundaries, but the olivine-rock near the contact is rich in garnet and diopside. This eclogite at times contains a very deep-green chrome-diopside, but in other cases it is pale light green and forms with the pale rose garnet a most delicate colour combinations. This garnet is often quite xenomorphic.

Another exceedingly beautiful rock is the tetramineralic combination garnet-diopside-enstatite-olivine, forming a few bands some ten centimeters thick with sharp boundaries. The three first-named minerals form an almost centimeter-grained crystal mass whose interstices are filled up with olivine. The same combination but with sparingly distributed crystals of garnet, diopside and enstatite in the ground-mass of olivine occurs as large masses all around the different segregations and was described under the olivine-rock.

The eclogite may pass over into garnet-diopside-enstatite-rock or enstatite-eclogite, found at several points. In one of these bands the diopside almost disappears and the mineral combination may be called an enstatite-garnet-rock. It contains small dark red garnets.

Diopside-garnet-olivine-rock, or olivine-eclogite, forms gradual transitions from the eclogite into the pure olivine-rock. Occurring in the same manner there was also found enstatite-garnet-olivine-rock and diopside-enstatite-olivine-rock.

The association olivine-diopside was found as small nodules with boundaries not sharply defined.

Olivine-garnet-rock without diopside was only found as an erratic boulder near Duestol.

Olivine-enstatite-rock or saxonite is fairly common and was described on p. 21. In the occurrence south of Duestol, this grades over into an enstatite-rock. At the same place the enstatite also was found as a fissure vein in which the long prisms of enstatite are arranged at right angles across the vein, like fibres of asbestos. It has been greatly altered into talc. This occurrence is remarkable as illustrative of the different appearance of all the other bands.

A nodule of pure chrome-diopside, about 30 cm thick, was found near Helgehornsvand. It is coarsely-crystalline and deep green in colour. From the surrounding olivine-rock it is isolated by a seam of enstatite.

Inclusions of pure garnet were found as very small nodules.

Most of the occurrences of eclogite in the olivine-rock are band-formed masses (fig. 5). Many of them could be taken for small intrusive sills or pegmatite-like primary veins of later crystallization than the main rock. At closer investigation it may be found that the bands are lenticular in shape though mostly very thin. Thick lenses and nodules or lumps, however, were also found. Moreover, though they have mostly sharp boundaries, they are surrounded by zones of olivine-rock in which the same minerals that form the bands occur as enclosed crystals.

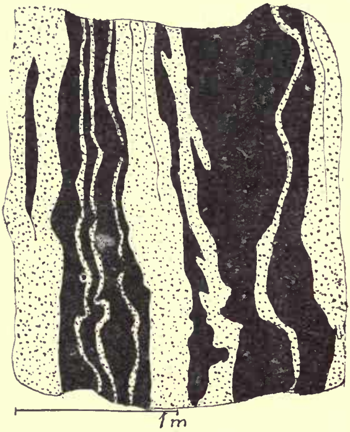

Fig. 5. Bands of eclogite (dotted) in olivine-rock (black). Rødhaugen, Almklovdalen.

Thus the mode of occurrence of this eclogite proves it to be genetically very closely connected with the dunite, but it does not, in itself, give any evidence as to which of the rocks has been formed earlier. Considering the monomineralic character of the dunite and the fact that at least diopside, the other chief constituent of the bimineralic eclogite, is a low-melting mineral as compared with olivine, it seems most probable that the bands, lenses and nodules of eclogite have crystallized after the dunite had separated.

Eclogite in olivine-rocks in other countries.

Eclogite as bands or nodules in olivine-rocks or in serpentines derived from the latter is of fairly common occurrence. A few examples may be abstracted from the literature dealing with this subject.

According to H. H. Müller[1] eclogite occurs as nodules in the serpentine near Greifendorf in Saxony, from fist up to head size, in places very profusely[1]. The eclogite passes over into serpentine. The same and some other occurrences (Zöblitz, Waldheim, Böhrigen, Geiersdorf, Molsdorf), were later described by J. Lemberg[1] and E. Dathe[2], and the eclogite is said to occur as "layers" (Schichten) stratified in the serpentine. The latter mostly contains crystals of garnet and diopside, the occurrence having an apparent resemblance to that in Almklovdalen. Near Heiersdorf the olivine is non-serpentinized (Dathe, loc. cit., 1876).

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[1] H. H. Müller, Geognostische Skizze der Greifendorfer Serpentin-Partie. N. Jahrb. Min. 1846, p. 266.

The garnet-bearing serpentines near Kremze in Southern Bohemian Forest were first described by F. v. Hochstetter[3], who states that eclogites occur in alternation with gneiss, serpentine, garnet-bearing hornblende-rock and coarse-grained granite. Later A. Schrauf[4] distinguished three main zones, called the zone of olivine-serpentine with pyrope and sparing omphacite, the zone of enstatite-omphacite and the zone of diallage-garnet-rock. The garnet of the last-named, apparently an eclogite, is said to be almandite. Unfortunately it is not clear from Schrauf's description, whether this rock occurs as inclusions in the olivine-serpentine or is associated with the gneiss. From Hochstetter's statements the latter relation seems more probable. But even if there are no eclogitic inclusions in the Bohemian pyrope-olivine-rock, their minerals, the pyrope and the chrome-diopside ("omphacite") are quite the same as those in the olivine-rock of Søndmøre.

Eclogites in the olivine-rocks also occur in the Forest region of Lower Austria. According to F. Becke[5] eclogite within serpentinized pyrope-olivine-rock crops out near Wauzenau and is found as boulders derived from pyrope-serpentine areas at Brünnel-Leiten and near Altenburg. Becke states the character of these eclogites as "Anhäufung derjenigen Minerale welche im Pyrope-Olivinfels akzessorisch auftreten: pyropähnlicher Granat, und ein oft durch Cr intensiv grüngefärbter monokliner Pyroxen". The same interpretation holds good in the case of the segregations in the olivine-rock in Søndmøre.

U. Grubenmann[6] studied the garnet-olivine-rocks in the Gorduno Valley. The crystals of garnet, which is a pyrope of the composition $Fe_{20}Mg_{66}Ca_{14}$, attain the size of a fist, but no aggregations of the eclogite-minerals are mentioned. Eclogite occurs at the peripheries of the rounded rock-mass surrounded by gneiss. The analysis of the eclogite proves that its garnet must be much richer in almandite than that in the olivine-rock.

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[1] J. Lemberg, Über die Serpentine von Zöblitz, Greifendorf und Waldheim. Zeitschr. d. deutsch. geol. Ges., 1875, 531.

[2] E. Dathe, Olivinfels, Serpentin und Eklogit des sächsischen Granulitgebietes, N. Jahrb. Min. 1876, 225 and 337.
E. Dathe, Berichtigung. Ibid. 1883, II, 89.

[3] F. v. Hochstetter, Geognostische Studien aus dem Böhmerwald. Jahrb. K. K. geol. Reichs-Anstalt, 1855.

[4] A. Schrauf, Beiträge zur Kenntniss des Associationskreises der Magnesiasilikate. Paragenetische Studien im Serpentingebiete des Südlichen Böhmerwaldes. Groths Zs. Kr. 6, 1882, 321.

[5] F. Becke, Das niederösterreichische Waldviertel. I. Übersicht der petrographischen Verhältnisse. T. M. P. M. 32, 1914, p. 206.

[6] U. Grubenmann, Der Granatolivinfels des Gordunotales und seine Begleitgesteine. Vierteljahrschrift d. Naturforsch. Gesellschaft in Zürich, 53, 1908.

In this connection we have still to mention the eclogite nodules in the diamond-bearing kimberlite of South-Africa. These are of the greatest importance for our subject and we shall have repeated occasion to refer to them. The literature dealing with these nodules is very extensive, but we do not need to abstract it, as a good monographical treatise is available[1]. The following data are quoted from the volume of Percy Wagner.

That variety of kimberlite poor in mica, building up the greater part of the pipes in which the diamonds and the nodules are found, has the following composition (p. 63): SiO_2 30.95, TiO_2 2.34, Al_2O_3 4.02, Fe_2O_3 6.16, FeO 2.66, CaO 8.92, MgO 32.30, MnO tr, NiO + CoO tr, Na_2O 0.35, K_2O 1.61, H_2O 7.36, CO_2 2.54, P_2O_5 0.15. Sum 99.36, Sp.g. 2.835.

The rock is composed of olivine (50—70 %), mica, pyrope, enstatite, ilmenite, diopside, perowskite, ores, apatite. As may be seen, this kimberlite differs from the pyrope-diopside-enstatite-olivine-rocks of Søndmøre only in the presence of mica and titanium minerals, and in the decomposed state of its olivine. The chemical nature is the same.

Wagner names 21 different mineral associations represented in the nodules. Of the minerals named by him the mica, ilmenite, apatite and cyanite are not met with in the segregations in the dunite near Lien. The other minerals, just as in the Lien inclusions, are garnet, diopside, enstatite and olivine, and most common in both is the combination diopside-garnet (eclogite) to which may be added enstatite or enstatite and olivine. The presence of diamond in some nodules in the kimberlite is of much interest.

The nodules are ellipsoidal, often flattened or almost tabular. Usually they are not more than 5 cm in diameter.

From this comparison a close analogy between the nodules in the diamond-bearing kimberlite and the band-formed masses in the Norwegian dunite is apparent. Difference occurs chiefly in the shape, but this is naturally accounted for by the different development: in one case volcanic explosions, in the other crystallization in connection with mountain-folding, whereby all the rock-masses have become stretched out and become thin bands.

T. G. Bonney, A. W. Rogers and A. L. Du Toit, F. P. Mennell, and certain other petrographers have interpreted the nodules in the kimberlite as fragments derived from some formation of eclogite existing at a great depth, while others, as R. Beck, Geo S. Corstorphine, R. Scheibe, F. W. Vogt and, though somewhat doubtfully, Percy Wagner, have seen in them segregations from the kimberlite magma. As a chief argument in favour of the former opinion the fact has been set forth, that these nodules, in their mineral composition, are perfectly similar to the true eclogites which, though with insufficient evidence, have been regarded as being of metamorphic origin, while the assumption of segregations from the kimberlite magma should postulate a primary crystallization from the magma. This argument loses its force, as we now find, in the Norwegian rocks, examples of "true eclogites" that are of primary igneous origin.

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[1] Percy Wagner, Die Diamantführenden Gesteine Südafrikas, Berlin 1909.

As another proof for his belief that the nodules are not genetically connected with the eclogites, F. P. Mennell[1] sets forth the difference in the composition of the garnets in the nodules and in the kimberlite, the former being richer in almandite. According to the analyses quoted by Mennell two eclogite-garnets from Colossus Mine, Rhodesia, have the compositions $Fe_{31}Mg_{36}Ca_{33}$ and $Fe_{18}Mg_{49}Ca_{33}$ respectively, while one of the garnet from the kimberlite leads to the formula $Fe_{17}Mg_{72}Ca_{11}$. In reference to this we may remark, that a similar difference also obtains between the garnet in the eclogitic nodules and bands ($Fe_{27}Mg_{61}Ca_{12}$) and in their dunitic country-rock ($Fe_{23}Mg_{65}Ca_{12}$) from Søndmore.

The perfect analogy with the masses of eclogite in our dunite also strenghtens the conclusion that the nodules of eclogite in the kimberlite are genetically connected with their country-rock, though not necessarily segregations of earlier date. Other evidences are: the extensive distribution and persistent characters of the nodules in the kimberlite pipes in South Africa, and also in N. S. Wales[2], the non-occurrence of other kinds of eclogite in the same region[3] and, above all, the occurrence of diamond in the nodules, even enclosed in the garnet. These evidences would seem to be conclusive in themselves.

In summary, the band-shaped masses of eclogite etc. in the olivine-rock in Søndmøre are crystallizations of igneous character connected with the country-rock and probably of a somewhat later date. Analogous masses of eclogite have been found in olivine-rocks of other regions and in the kimberlites of the diamond-bearing pipes.

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[1] F. P. Mennell, The Geological Structure of Southern Rhodesia. Quart. Journ. Geol. Soc. 66, 1910, p. 353.

[2] George W. Card, An Eclogite-bearing Breccia from the Bingera Diamond Field, Rec. of the Geol. Surv. of N. S. Wales, 7, 1902, 29—39.

[3] F. P. Mennell (loc. cit.) mentions that eclogite should occur in pre-Cambrian schists around granite massifs. As, however, no characteristics are given, it is not sure that a true eclogite, and not e. g. garnet-amphibolite or diopside-grossularite is in question.

The Eclogite in the Gneiss.

Mode of occurrence.

In many parts of the gneiss area in Nordfjord and Møre inclusions of eclogite occur in great numbers. They are all small. I do not know any continuous mass over 100 meters in the longest diameter. In describing their mode of occurrence we may first quote (in translation) what Dr. H. Reusch, in his unpublished notes of 1883, writes in an account of the eclogite on the island Silden in Selje, west of the island Barmen:

"On the east side of the island there occur, in a moderately garnetiferous grey gneiss, a few lenses which, in their central part, consist of eclogite, towards the boundaries passing over into a hornblende-rock. The eclogite is banded owing to various proportions of the garnet and pyroxene." (Fig. 6.)

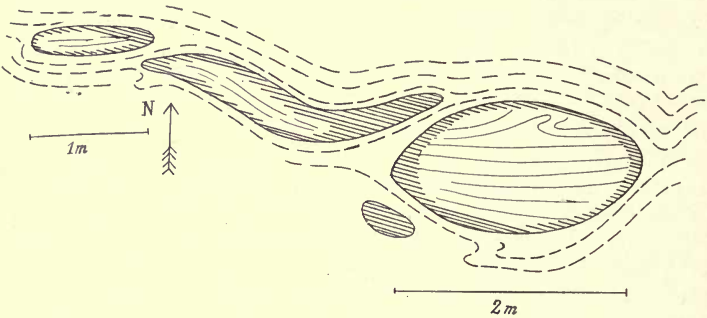

Fig. 6. Lenses of eclogite with boundary-zones of amphibolite. Silden, Selje. After H. H. Reusch.

A specimen from the one meter long lens served as material for my quantitative investigation (p. 37). Reusch continues:

"Somewhat towards the North from the farm-house N. Silden another larger mass of eclogite rises up from the sea" (Fig. 7). "The elongated prisms of the pyroxene are arranged parallel, giving the rock a pronounced foliation which dips 30° towards the East and is also apparent in the surrounding gneiss. At right angles to the foliation the rock is cut by joints, in part filled up with quartz. Beginning from these joints the rock has altered into a hornblende-rock, some 25 or 30 cm at both sides. The eclogite contains some quartz and mica; of these the former appears unchanged in the altered zones, while the mica disappears. The eclogite passes gradually over into the hornblende-rock, as is also the case along the boundaries where a zone of the latter invariably occurs."

This very conspicuous alteration into amphibolite (the altered rock consists of hornblende and plagioclase) which is a constant feature of the eclogites in the gneiss, will be discussed in a special chapter.

I had myself good opportunity to study the inclusions near Bryggen in Nordfjord. The main rock is a stretched-out veined gneiss, in which frequent lenses of eclogite or amphibolite are enclosed. Fig. 8 shows such lenses, the larger of which, in their central parts, consist of almost non-foliated fine-grained eclogite rich in pyroxene surrounded by thick zones altered into amphibolite. Smaller lenses are entirely composed of amphibolite and, as may seem probable from the analogy, it is wholly evident from the relict features, that these have been primarily lenses of eclogite, now perfectly altered into amphibolite.

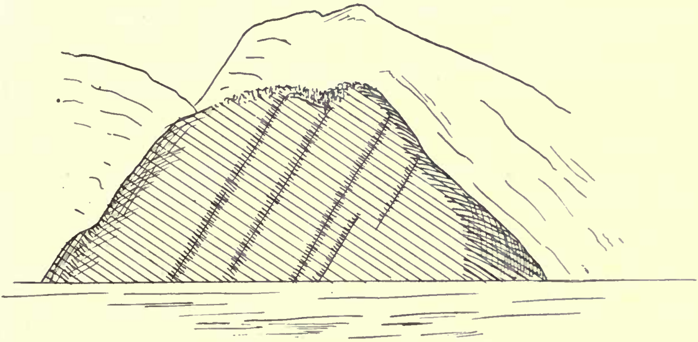

Fig. 7. Eclogite as a larger mass in gneiss, with zones of amphibolite at the boundaries and on joints. Silden, Selje. After H. H. Reusch.

Other lenses have no amphibolitic border-zones; these contain only amphibole besides the garnet which is almandite, and the rock is thus an almandite-amphibolite, stable in the amphibolite facies.

At two places near Bryggen were observed larger masses of fine-grained amphibolite which contains a few portions of eclogite enclosed. It appears here that all the amphibolite once was eclogite. That it has here been amphibolitized throughout such large masses may be understood in connection with the fact that thin lenses or veins of quartz have been injected into the amphibolite. This amphibolite is a pavement-like mixture of green hornblende and plagioclase with quartz and biotite and zoisite and, occasionally, margarite. Crystals of garnet may occur.

Near one of these places, about 300 meters west of Bryggen, the rock has developed into a veritable eclogite-adergneiss. The veins for the most part consist of quartz-garnet-rock or pure quartz, though true aplitic veins also occur.

It would be of great interest to know whether all the basic inclusions in the gneiss are — or once have been — eclogite. I studied the fairly well exposed shore-rocks near Bryggen rather carefully and soon arrived at the conclusion that such is the case, excepting some coarse-grained dioritic fragments, of a more acid composition than the eclogites. Some of them are now composed mainly of biotite and epidote. All the more basic fragments show eclogitic kernels or, if entirely amphibolitized, prove by their structure to be altered eclogite.

Inclusions of eclogite, more or less amphibolitized, were found in all the varieties of the gneiss: in the almost non-foliated gneiss-granite as well as in the veined and banded gneisses. In some tracts, however, no eclogitic inclusions can be found. Thus I walked four kilometers from Torsvik to the church of Vanelven and almost 20 kilometers from Almklovsaeter to Omelfot near Dalsfjorden without seeing any one enclosure of eclogite. In one case the reason was, that there are no basic inclusions whatever, and in the other case, that all the eclogites have been thoroughly amphibolitized — or primarily consolidated as hornblende-gabbros. The arteritization, or development of veins, was here too effective during the last stage of consolidation of the gneiss, and the result was a migmatite in which the older portions are hornblende-bearing gneisses.

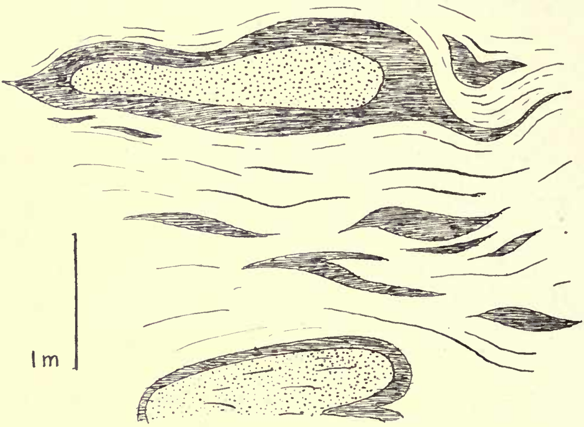

Fig. 8. Lenses of eclogite with boundary-zones of amphibolite. Small lenses have altered thoroughly into amphibolite. Bryggen, Nordfjord.

By this I do not mean that such mixed rocks would necessarily have contained inclusions of eclogite, but that their amphibolitic portions have some genetic similarity to such inclusions: What in one case appears as lenses of eclogite and in the other case as schliers and bands rich in hornblende, is genetically one and the same thing.

From the occurrence of the eclogite as lenticular inclusions in the igneous gneiss it follows, that they must have consolidated earlier than the gneiss. A remarkable exception to this rule, however, was met with on Seljenaes, near the occurrence of margarite-bearing orbicular labradorite-rock described later on.

About 100 meters south of Seljenaesholmen there is, on the low shore plain, an occurrence of eclogite bounded directly by augengneiss. The eclogite contains some rounded fragments of the latter. The gneiss has hereby been altered in the most peculiar way: Small fragments have been changed entirely into a mass of mica, for the most part muscovite. The same is the case with the central zones of the larger fragments, but towards the centre the latter pass gradually over into a rock in which some feldspar and, in the very largest, a little of the eye-structure may still be seen. In the eclogite, on the other hand, there is a narrow "endogenous" contact-zone, in which the rock has been amphibolitized. In some cases the boundary-zone is rich in garnet.

This occurrence may be interpreted in one way only: Fragments of the eyed gneiss, already consolidated, had been detached from the large mass by the eclogite magma and been enclosed in it. The temperature of the latter, however, was high enough to cause the refusion of the quartz-feldspar (eutecticum?) of the gneiss; this molten mass was squeezed out and the mica alone remained and was clustered into a compact mass.

Exceedingly interesting as the phenomenon is, it is, however, an exception. Hundreds of other occurrences of eclogite are obvious inclusions in the gneiss, and there is no way open to explain them as intrusions, nor is it possible to apply the explanation used by J. J. Sederholm[1] in assuming primarily basaltic dikes, when their country-rock had been refused, to have been converted into series of inclusions of amphibolite. As a rule, the lenses are true inclusions in the gneiss.

The importance of the Seljenaes occurrence lies in its evidence that an opposite case also was physically possible: that once, in connection with the great orogenetic movements, a solid gneiss mass was pressed down deep enough to meet gabbroid magma which, after having enclosed fragments from the gneiss, solidified as a true eclogite.

The inclusions of Eclogite compared with other "dark Inclusions" in Gneiss or Granite.

The inclusions of eclogite, in the gneiss of More and Nordfjord, play the same rôle as the so-called basic or "dark" inclusions in many other masses of granites and gneisses. The last-named inclusions, if they are not eclogites, as is a common case in many lands, generally consist of rocks that may be petrographically characterized as amphibolites or diorites or hornblende-gabbros. Their mineral composition almost without exception conforms to the amphibolite facies.

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[1] J. J. Sederholm, Om Granit och Gneis. Bull. Com. géol. Finl. 23. 1907.

Now, it is possible that, in many cases, such inclusions have once consisted of eclogites, while in other cases such a supposition would have no reason. In any case, all such inclusions, eclogitic as well as amphibolitic, are analogous in being "basic" aggregates of gabbroid composition enclosed in granitic rocks.

One would therefore suspect a close genetic connection, a consanguinity, between the inclusions and their country-rock and, in some cases, this is very obvious in fact. Such is the case in the so-called anticlinal batholiths[1] in the Fenno-Scandian Archaean, to which belongs the Orijärvi granite studied by the present writer. As I have set forth[2], the dark inclusions are probably fragments from the gabbro-dioritic portions of the batholiths consolidated earliest as the boundary-zones of the mass.

In the present case this theory, however, can hardly be applied in such a simple form. It is not possible to state with certainty the mechanism of intrusions and differentiation of such gneiss-masses as that of Nordfjord and Møre. But one is sure that fluctuations on a large scale, caused by the effective stress, have taken place in the crystallizing and differentiating gneiss magma. Although a consanguinity relation is probable and the process of differentiation of the gneiss, as a whole, may have been owing to the gravitative control in the manner emphasized by R. A. Daly[3], there may have been chances for the inclusions to be caught up from beneath as well as to sink down from above.

The question now arises, whether the inclusions have consolidated within the gneiss magma, as must be assumed in the case of the eclogite in the olivine-rock, or have been detached from larger consolidated eclogite-masses. Unfortunately the field evidence, on this point, is not quite conclusive. If the inclusions were concretions, or aggregations of crystals separated out from the magma, they should show concentric structures. Some kind of concentricity may actually be noted in smaller fragments, appearing in a concentric foliation, or in the enrichment in the salic constituents of the amphibolitized border zones, but these are probably all due to later influences, as is the amphibolitization itself. Most of the small lenses, in their unaltered portions, are quite non-foliated.

Band-structure is very common in the inclusions, being always parallel to their elongation. I never observed that the banding would conform to the lens-form at the ends of the lenses, though I can no more state that this structure would have been cut off. Further observation with special attention paid to this point, could perhaps give full elucidation.

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[1] Per Geijer, On the Intrusion Mechanism of the Archaean Granites of Central Sweden. Bull. Geol. Inst. University of Upsala, XV, p. 47, 1916.

[2] Pentti Eskola, On the Petrology of the Orijärvi Region. Bull. Comm. geol. Finl. 40, 1914, p. 64.

[3] R. A. Daly, Igneous Rocks and their Origin. 1913.

The markedly banded eclogite near Aaland, Bryggen, builds up a little peninsula, and the ends are not exposed. The series of bands, on the southern side, begins with alternating garnet- and pyroxene-rich bands, a few cm thick, whereafter follow amphibole-eclogite and more massive varieties of pyroxene-eclogite. The lens, as a whole, has an unsymmetric structure.

A lens of banded eclogite on Aasnaes near Bryggen is 15 meters broad and apparently very long, only a section on the shore being exposed. The individual bands, many of which are almost monomineralic, are but one or two centimeters thick. Somewhat broader bands of amphibole-eclogite occur on the northern salband, giving the occurrence an unsymmetric appearance.

H. Reusch (op. cit. 1877) described a large outcrop of banded eclogite near Søndre Vartdal. No concentric arrangement of the bands has been mentioned. Nor have I found any such note in the literature concerning very similar banded eclogites in igneous gneiss in other lands.

Many small inclusions, have an unsymmetric structure. Most illustrative is the occurrence of eclogite-pegmatite at Grytingvaag (p. 49). This inclusion, showing a part of a large pegmatitic dike and a portion of its country-rock on the one side, can hardly be understood in any other way than as a fragment derived from a formerly consolidated complex.

Many inclusions, moreover, show quite irregular forms.

In this respect the inclusions of eclogite are similar to the "dark inclusions" in the Archaean granites and granite-gneisses, and both must be regarded as genetically analogous.

There is, on the other hand, full evidence that the eclogite has consolidated under similar stress conditions as the gneiss: We must remember the very existence of banded structure apparently originated by fractional crystallization during fluctuation under stress, just as did the analogous band and vein structure in the gneiss itself. This band structure, in the eclogites, gradually passes over into a foliation by parallel arrangement of the crystals, and further into a protoclastic structure from which a further step leads into a true eclogite-mylonite. The banding and foliation is always conformable to the strike of the adjacent gneiss.

But along-side with this apparent connection between the lenses and their country-rock, the former often prove not to have been originated in situ: Perfectly non-foliated eclogite may be found enclosed in the ultimately stretched out gneiss, and inclusions of eclogite of quite different structure may be found near one another.

The field-evidence so far gathered goes to favour the opinion that the inclusions of eclogite are no segregations crystallized within the gneiss magma, but more probably true fragments detached from larger bodies of eclogite-rocks. They have, however, originated under the same conditions as the gneiss and been subjected to stress during their consolidation, hereby pointing to a probable genetic connection, a consanguinity, to the latter. They are identical in bulk composition, analogous in the mode of occurrence and, most probably, similar in the origin with the "dark inclusions" so common in many granites and granitic gneisses.

Eclogite in Gneiss in other Countries.

In a previous chapter were mentioned, from the literature of the subject, several occurrences of eclogite directly connected with the olivine-rocks. Here it will be useful to give a review of the occurrences enclosed in gneissic rocks.

Perhaps the best-known eclogite-bearing gneiss mass is that of Münchberg in the Bavarian Fichtelgebirge. It is one of those batholiths in Central Europe formerly regarded as belonging to the pre-Cambrian "Grundgebirge", but later found to be intrusive in the paleozoic sedimentary series, as at first was emphasized by C. F. Naumann[1]. The Münchberg eclogites were investigated petrologically by Ernst Düll[2], his field and microscopic studies being the most careful and detailed so far published about any eclogite-bearing area.

The Münchberg eclogite occurs, at very numerous places, as lenses in the gneiss, its outer appearance and parting recalling igneous rocks. All the lenses are surrounded by amphibolitic zones, interpreted by Düll as originated by the alteration of the eclogite. Some resorption has taken place on the boundaries, and smaller inclusions have been entirely resorbed giving rise to schlieric hornblende- and mica-gneiss. The resorption bands are elongated in the strike. Banding in the eclogite often occurs due to unequal distribution of garnet and pyroxene. In all these characters a perfect similarity to the Norwegian occurrences is evident.

Düll distinguishes between orthogneiss and paragneiss, but the latter, in his nomenclature, is simply an igneous gneiss containing appreciable amounts of resorbed materials. It is not a sedimentogenous gneiss.

Besides eclogite the Münchberg gneiss also contains inclusions and larger masses of amphibolite.

Mineralogically the Münchberg eclogites differ from the Norwegian rocks in containing cyanite. The other constituents are the same.

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[1] C. F. Naumann, Ueber die Münchberger Gneissbildung. N. Jahrb. Min. etc. 1863, p. 1.

[2] Ernst Düll, Ueber die Eklogite des Münchberger Gneissgebietes. Geognostische Jahreshefte, 15, 1902.

I had specimens of the Münchberg eclogites from Silberbach Hof, and Weissenstein for comparison. Structurally they are all most like the Duen type, though, in the foliation of the ground-mass, they approach the Silden type. The garnet, unlike most of the Norwegian eclogites, contains inclusions of quartz.

In the Münchberg gneiss area also occur masses of serpentine[1].

Another eclogite-bearing tract is the gneiss and granulite area of Saxony. These formations also had been interpreted as intrusive in the Palezoic formations by C. F. Naumann, but later H. Credner, E. Dathe and others re-accepted the Wernerian idea of a pre-Cambrian age of this basement gneiss. The problem, as regards the gneiss, was settled by C. Gäbert[2] who gave conclusive evidence of its igneous and intrusive nature. Some occurrences of eclogite are associated with the olivine-serpentine-rocks, but far more numerous are those forming inclusions in the gneiss. A. Sauer and F. Schalch[3] enumerate 54 occurrences either directly enclosed in the gneiss or surrounded by amphibolite.

In the Lower Austrian Forest region eclogite, according to F. Becke[4], occurs in (igneous) gneiss as well as in the olivine-rock. The former always stands in close connection with hornblende-rocks.

H. B. Patton[5] found eclogite surrounded by a zone of ampibolite, embedded in gneiss at Grün near Marienbad in Bohemia. Olivine-rock also occurs.

The eclogites of Saualps and Koralps in Carinthia have been described by M. V. Lipold[6]. They occur as inclusions (Einlagerungen) embedded in the gneiss parallel to the foliation.

In the Back Alps[7] the eclogite is enclosed in granulite and garnet-bearing gneiss along with serpentines (diallage-serpentine and diallage-rock). The eclogites are accompanied by amphibolites.

In the Mont Blanc region eclogites, associated with amphibolites and serpentines, are found within the crystalline mantle which surrounds the mass of protogine[1]. The main rock of this crystalline mantle is regarded as paragneiss[2].

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[1] C. W. Gümbel, Ueber das Alter der Münchberger Gneiss-Partie im Fichtelgebirge. N. Jahrb. Min. etc. 1861, 257.

[2] C. Gäbert, Die Gneise des Erzgebirges und ihre Kontaktwirkungen. Zeitsch. d. deutsch. geol. Ges. 1907.

[3] A. Sauer und F. Schalch, Ueber die Verbreitung des Eklogites im SW-Theile des Erzgebirges. N. Jahrb. Min. etc. 1884, II, 27.

[4] F. Becke, Die Gneissformation des niederösterreichischen Waldviertels. T. M. P. M., 1882, 317.

[5] H. B. Patton, Die Serpentin- und Amphibolgesteine nördlich von Marienbad in Böhmen. T. M. P. M. 9, 1888, 124.

[6] M. V. Lipold, Die crystallinen Schiefergesteine in nordöstlichen Kärnthen. Ref. N. J. 1858, 222.

[7] J. A. Ippen, Zur Kenntniss der Eklogite und Amphibolgesteine des Bachergebirges. Mittheilungen d. nat.-wiss. Ver. f. Steiermark, 1892. Ref. N. Jahrb. 1894, I, 461.

The massif of Aiguilles Rouges is, according to the Swiss geologists[3], composed of old highly metamorphic sediments (Gneiss, Glimmerschiefer), mainly in the form of hornfels, the petrosilex of de Saussure. Eclogites are found near Lac Cornu. In their vicinity there occur a number of lenses of serpentine[4]. Amphibolitization of the eclogites is most perfect at the contacts.

Laura Hezner published a careful investigation of the eclogites in Ötztal, Tirol[5] and especially paid much attention to the alteration of the eclogites into amphibolites. This process, according to Hezner, always works inwards, beginning from the margins, and therefore the masses of eclogite are surrounded by zones of amphibolite. These masses are embedded in a paragneiss which has not been studied more in detail.

All these occurrences of eclogite — and still others could be mentioned — are no doubt very similar to each other and to the Norwegian eclogites in their mode of occurrence and general characters. Of these the Swiss and Tirolian eclogites are said to occur as inclusions in sedimentogenous gneiss[6], while all the other have been regarded as igneous gneisses. Other eclogitic rocks are interbedded in series of micaschists, marbles and other metamorphic rocks of para-character[7]. At present we may state, as a summary on the occurrence of eclogites in gneiss, that a large number of them are inclusions in igneous gneiss.

On the Genetic Connection between the Eclogites, Dunites and Labradorite-rocks.

As we have seen, some of the eclogites occur as inclusions in the olivine-rocks, while others are inclusions in the gneiss and do not show any direct connection with the olivine-rocks or the labradorite-rocks. Many occurrences, however, afford a sufficient evidence that these three kinds of rocks are genetically connected with one another, even in such cases where they form separate inclusions or intrusions in the gneiss. I shall describe a few examples.

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[1] L. Duparc et L. Mrazec, Recherches géologiques et petrographiques sur le massif du Mont Blanc. Mém. Soc. Phys. et Hist. nat. 1898.

[2] Albert Heim, Geologie der Schweiz. Band II. Leipzig 1920, p. 219.

[3] Op. cit. p. 232.

[4] E. Joukowsky, Sur les Eclogites des Aiguilles Rouges. Thése, Genéve 1902.

[5] Laura Hezner, Ein Beitrag zur Kenntniss der Eklogite und Amphibolite, mit besonderer Berücksichtigung der Vorkomnisse des mittleren Ötztales. T. M. P. M. 22, 1903.

[6] In the paragneisses of Mont Blanc and Aiguilles Rouges intrusive material is also present (Joukowsky, op. cit.). It would seem probable to the writer that such might possibly also be the case with the other alpine paragneisses here in question and in such a case perhaps the mode of occurrence of the eclogite would not be materially different from that of the inclusions in igneous gneisses.

[7] Cf. "The Mineral Facies," p. 184.

Sølvbergknausen, Dalsfjord, Søndmøre. Near Stensvik at Dalsfjord labradorite-rock covers a rather large area on the mountain slope. In a section visible in Sølvbergknausen near Omelfot (fig. 9) it appears as sheet-shaped masses in an inclined position parallel to the strike of the surrounding gneiss. In fig. 9 only the lowest sheets of a larger series are visible; other much thicker masses ot labradorite-rock follow upwards.

Beneath the labradorite-rock follows a thinner sheet of eclogite, largely amphibolitized and, in turn, underlain by sheets of dunite and saxonite, bounded by the gneiss.

At the contact the labradorite-rock passes over into (amphibolitized) eclogite in such a way that its mafic minerals, to which is added garnet, become gradually more copious and cluster into enclosed lumps. The labradorite-rock is distinctly younger and the mixed rock, at the contact, has often developed as an eruptive breccia. The whole appearance has much resemblance to the relations of eclogite and labradorite-rock in the Bergen region.

Near Ekremsaeter, Almklovdalen, a sheet, or sill, of labradorite-rock (p. 23) begins from the border of the large body of olivine-rock and stretches eastward in the gneiss-area parallel to its strike. On its north side this mass is bounded by numerous large masses of eclogite, some of which are 50 m thick. This eclogite is coarse and well preserved, but contains epidote.

Duestøl. In the rocky hill SE of Duestøl in Almklovdalen chloromelanite-eclogite of the Duen type, often much amphibolitized, alternates with feldspar-bearing rocks intermediate between the eclogite and the labradorite-rock. The specimens studied in thin sections contained plagioclase (about Ab_{50}), clinopyroxene (altered into diopside-plagioclase-symplectite or a symplectic plagioclase-hornblende-mass), enstatite, garnet, quartz and epidote-minerals. Locally they pass over into pure labradorite-rocks and, in the continuation of this rock-zone along the strike, there is a large body of labradorite-rock near the Almklov farm. Here also many smaller masses of eclogite occur in its neighbourhood.

The occurrence near Duestøl is, on both sides, bounded by dunite and saxonite, only locally exposed. Thus the field connection of the three rocks is quite apparent.

The margarite-bearing orbicular labradorite-rock on Seljenaes, Nordpoll, Selje. This is an occurrence of a very peculiar rock and would deserve a special treatment. Here I shall only give a short description of its unique characters, and mainly as an illustration of the intimate connection between the labradorite-rock and the eclogite.

Some specimens of the orbicular labradorite-rock from Seljenaes were collected in 1886 by Dr. H. Reusch, who called the rock a pseudoconglomerate. No microscopical examination had been undertaken, and the occurrence has not been mentioned in the literature. My attention was drawn to these specimens kept in the collections of the Geological Museum of Christiania, and later I had an opportunity of visiting the locality.

The orbicular labradorite-rock occurs in low shore cliffs near the Seljenaes farms at Nordpoll in Selje. The very best outcrop is a little island called Seljenaesholmen. In the northern part, next the farm-houses, the main rock is a foliated labradorite-rock of the common type in this region. It passes over into the orbicular variety, small rounded lenticular nodules appearing in the homogeneous rock. From the ground-mass these nodules first differ only in being lighter in colour, due to the absence of mafic compounds, and in a somewhat finer grain. They may be of the size of peas, but locally they have a longest diameter of about 5 cm. Such larger nodules often contain margarite as their main constituent, and sometimes their inner parts are composed of wollastonite. These inner cores of wollastonite have somewhat irregular forms, and the nodules, though they have smooth surfaces and rounded shapes, do not show any regular concentric structure. Minerals of the epidote group are often abundant.

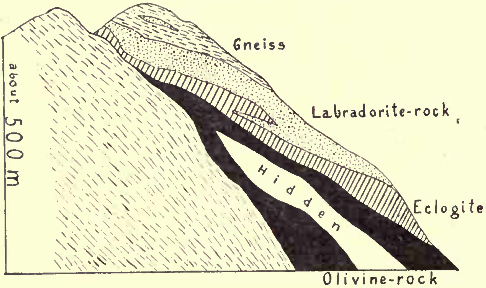

Fig. 9. The section in Sølvbergknausen, near Omelfot, Dalsfjord, Søndmøre.

The ground-mass always is distinctly foliated, and the whole rock is banded, the size of the nodules in each band or lens being rather invariable. Lenses of eclogite are commonly enclosed, and they sometimes pass over into the orbicular rock: some nodules appear in typical eclogite, and labradorite gradually replaces the eclogite-constituents. Fig. 10 illustrates an outcrop on Seljenaesholmen, showing lenses of a true eclogite and larger bands of an intermediate type, an eclogitic rock containing nodules of the same kind as those in the labradorite-rock. This eclogite is greatly amphibolitized, and may fade over into a schistose amphibolite, rich in biotite and epidote or zoisite.

The following notes on the microscopic characters do not by any means tend to be exhaustive. It may be hoped, that this interesting occurrence will be investigated more in detail.

The ground-mass of the orbicular labradorite-rock consist of plagioclase, hornblende and zoisite.

The plagioclase in the ground-mass is decimillimeter-grained and shows a marked inverse zonal structure. The more albitic cores have rather sharp limits towards the more anorthitic boundary-zones. The composition varies from Ab_{72} to Ab_{45} (cf. p. 25).

The hornblende occurs as small prisms of green colour similar to those in other labradorite-rocks in this tract. The zoisite forms somewhat larger prismatic crystals.

The nodules are either composed merely of plagioclase or of margarite and wollastonite, and often zoisite, besides smaller amounts of light mica and plagioclase.

The plagioclase, in the nodules, appears as a fine-grained mass with serrated outlines of the individuals. In its composition it is similar to the more anorthitic portion of the plagioclase of the ground-mass.

The margarite is megascopically of a faintly reddish colour. The scaly individuals are embedded either in plagioclase, wollastonite or a fine mass of colourless mica. They often are twinned on (001), the extinction in sections normal to the cleavage being distinctly oblique (in maximum 6°); $\beta = 1.645 \pm 0.003$. The negative acute axial angle is of the same order of magnitude as that in many varieties of muscovite, while the birefringence is much lower. Sp. g. = 3.024. I tried to separate the mineral with heavy solutions, but did not succeed, much adhering mica being left. A partial analysis of this material showed a composition conformable to that of some mixture of margarite and muscovite.

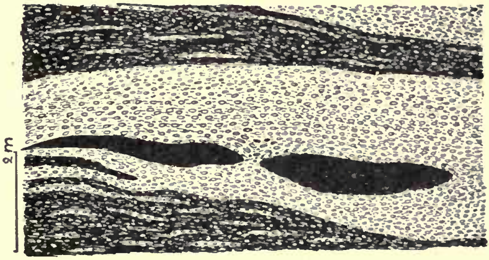

Fig. 10. Orbicular labradorite-rock with lenses of eclogite (black) and a transitional rock between eclogite and the orbicular labradorite-rock (black with white dots). Seljenaesholmen, Selje, Nordfjord.

The wollastonite forms a granular mass of somewhat larger grains than all the other minerals. They are speckled with inclusions of margarite, light mica and zoisite. Diagnostic characters are the cleavage and a negative optic character with $2V = 45°$ appr.

The mica shows the characters of ordinary muscovite.

The quantitative proportions of the minerals in the nodules are rather variable, but, on the whole, the margarite is the most abundant in most of them and gives the rock its peculiar chemical character. This mineral contains over 50 percent alumina, and thus the bulk composition also is characterized by a high exess of alumina, besides a low amount of silica, and much lime.

It may be asked: how have these nodules originated? The presence of wollastonite could suggest the hypothesis of silicified inclusions of limestone, detached by the labradorite-rock magma, but the regular distribution of the nodules and their almost equal size in each band-shaped portion of the rock is very little in favour of this supposition. This question must therefore be left open.

No olivine-rocks were met with in immediate connection with the eclogite and labradorite-rock on Seljenaes, but not far from this locality such rocks are exposed near Sørpoll.

As a general summary, it is clear from the above examples, that the olivine-rock, the eclogite and the labradorite-rock are in some way genetically connected with one another. But, while the two first-named rocks are older segregations in the gneiss, the labradorite-rock no doubt behaves as a rock solidified later than the gneiss-masses. It also shows another mineral development, or another facies, than the eclogite.

In the case of the eclogites from the Bergen region we shall meet with a similar relation between the labradorite-rocks, the eclogites and the olivine-rocks, still more accentuated. All these rocks no doubt have been derived by a process of differentiation from one and the same magma, but the details or causes of this process we may at present leave undiscussed.

Alteration of the Eclogite.

The Myrmekite-like plagioclase-diopside-symplectite formed from the clinopyroxene.

The most common posterior change in the eclogites is the breaking up of the eclogite-pyroxene into diopside and plagioclase.

But eclogites enclosed in the olivine-rocks are entirely free from this kind of alteration. This is what could be expected, as the clino-pyroxene in these is already primarily a diopside, almost devoid of alkalies and alumina.

In the following we shall make acquaintance with this phenomenon by means of a few examples, beginning from its first appearance.

In the eclogite from Silden (fig. 4, pl. I) the alteration appears only as extremely narrow dull, as though dusty, boundary zones around the pyroxene grains. Examined with a high power objective this zone is seen to contain pigment-like particles.

The following stage was observed in a coarse-grained eclogite from the island Lille Rødholmen near Haram. The altered zone is seen to contain thread-like particles arranged at right angles to the boundaries.

A little farther developed we find the phenomenon in the chloromelanite-eclogite from Vanelven (analyzed p. 31, fig. 2, pl. I). The altered zones attain a breadth of 0.1 mm and the threads, which are here seen to consist of an individual, colourless birefracting mineral, may be 0.005 mm thick and have curved forms, like the quartz-threads in the plagioclase-quartz-myrmekite. The intergrowth is chiefly confined to the boundary-lines, but at places these zones grow thicker and send out bays into some of the limiting pyroxene-grains. The ground-mass of the intergrowth may here be determined as clinopyroxene, having the same refringence as the adjacent chloromelanite and a positive axial angle of about 60°. On the boundary-line between two pyroxene grains, all the intergrown pyroxene is individual and forms the continuation of one of the pyroxene grains.

In another specimen of the chloromelanite-eclogite from Vanelven the zones of intergrowth show a more decided tendency towards sinuous development, and the rule was found to hold good that the sinuous portions belong to those individuals from which they have grown out, and not to those towards which their convex sides are directed.

In a specimen from Langeland, Sunelven, the sinuous intergrowths occupy a large part of the pyroxene mass, in another marked Gurskø (fig. 7, pl. II) almost a half. The intergrowth invariably is coarsest at the basis of a sinus where its growth had started, and, towards its convex margins, or the front of the gradually protruding sinus, it becomes ever finer and, at the very margin, resumes the dusty appearance characteristic of its incipient state.

At this advanced stage zones of intergrowth frequently appear to have begun to grow from the boundary line to each of the limiting individuals and do not belong to any of them. Careful observation, however, shows that they then have started from some other neighbouring individual.

In a specimen from Leinekiven, Bøland, the intergrowth has replaced the greater part of the pyroxene (fig, 8, pl. II).

The development of the secondary intergrowth was, in several specimens, followed to even more advanced stages. The grains seem to eat one another, the individuality of every grain becomes transported to some of its neighbours, at the same time as the myrmekite-like intergrowth developes. That stage, where no unaltered clinopyroxene was left, but still no other change had been induced, was found almost attained in a specimen from Saetre on Hareid (fig. 9, pl. II). As follows from the mode of growth, an individual of pyroxene, at this stage, mostly limits by its finest front side to the coarsest basis side of the adjacent individual.

The "threads" or "rods" forming the minor part of the intergrowth, attain, in the specimen from Leinekiven, a breadth of 0.01 mm. In refringence and birefringence they conform to plagioclase; no twinning was ever observed. Within a definite individual of pyroxene all the rods belong to one and the same individual of plagioclase. In their real shape they are tabular and folded and not threads or rods, as they appear in thin sections.

In all the specimens so far described amphiboles occur only as kelyphitic shells (green hornblende) around the garnet and occasional large grains (colourless actinolite); they show no connection whatever with the myrmekite-like intergrowth.

When all the pyroxene has been changed into the intergrowth, this may continue to grow coarse, and the difference between the front and the basis tends to disappear. A specimen from Hegerskjaeret, Hustadviken, represents this final stage of development (fig. 10, pl. II). The pyroxene shows $2V\gamma = 60^\circ$. In this case the plagioclase sometimes shows twinning lamellae and, in sections $\perp$ M, a maximum extinction angle of 10°. It is an oligoclase-andesine.

This is the most peculiar kind of alteration in the Norwegian eclogites enclosed in gneiss. I will call the myrmekite-like intergrowth a symplectite, according to the proposition of J. J. Sederholm[1].

Structurally this intergrowth shows the most remarkable resemblance of the common quartz-plagioclase-myrmekite. Many other kinds of such symplectites have been observed (summarized by Sederholm, op. cit.).

The present case deserves a special interest because the origin of this diopside-plagioclase-symplectite is perfectly clear from the point of view of the facies-theory: The jadeite-bearing pyroxene became unstable, when the pressure was reduced, and was replaced by the alkali-free diopside and the soda-lime feldspar. It is true that the diminution of the percentage of soda in the newly crystallized pyroxene has been not proven by any positive determination; its axial angle in the chloromelanite-eclogite seemed to be smaller than that of the chloromelanite, but I was unable to measure it exactly. But considering the constant occurrence of this phenomenon in the jadeite-bearing pyroxenes and its absence in the jadeite-free pyroxenes from the eclogites in the dunite, and further the fact that the feldspar makes up a smaller part of the intergrowth, just as jadeite in the unaltered pyroxene, the above interpretation cannot be denied.

It is not clear, why the alteration has chosen such a curious way of replacement and not a simple breaking up and separation of plagioclase, as is the case in the solid solutions of feldspar: the perthite. This kind of alteration, however, was also observed, being represented in specimens from Gimnaes and from Trekrem near Tingvold, both localities in Nordmøre. In these the plagioclase has been separated out at the same time in the whole of the pyroxene mass, in the former in long and almost linear rods parallel to axis c.

This specimen from Gimnaes also shows incipient uralitization, green hornblende forming zones around the pyroxene in homoaxial arrangement.

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[1] J. J. Sederholm, On Synantetic Minerals and related Phenomena. Bull. Comm. géol. Finl. N:o 48, 1916, p. 46.

In the specimens showing rather coarse plagioclase rods in the symplectite an incipient amphibolitization may often be observed. This alteration begins from the kelyphite rings and developes further along the boundaries between the diopside-grains. Its effect is to produce a granular mass of plagioclase and green hornblende, in which biotite may also be present.

We have above taken examples of the different stages of the recrystallization from various localities, as they presented themselves during the work. To prevent misunderstanding, it must be pointed out that all the stages were also found in rocks from a very limited area in Almklovdalen, and they are no doubt to be found at every occurrence of eclogite, as well as also the further alteration into amphibolite.

The diopside-plagioclase-symplectite is doubtless widely distributed in the eclogites, although very few petrologists have been aware of it. F. Becke[1] first noted it from the Forest region of Lower Austria, and gave an exact description of its characters.

P. Lohmann[2] observed the zones of alteration around the pyroxene in many eclogites and also in some specimens from Norway, but he did not determine its components.

A. Lacroix[3] described the alteration of clinopyroxene into an intergrowth of hornblende and plagioclase in eclogites from Loire inférieur, very like that which we, in the Norwegian eclogites, will find as a further alteration of the diopside-plagioclase-symplectite. Later S. Franchi[4] found an analogous phenomenon in eclogites and eclogitic micaschists from the region of Biella and called it feldspar-uralitization. It seems probable to me that many petrographers, after these observations, have taken pyroxene in the finest intergrowths for amphibole. I have a specimen of eclogite from Saint-Philbert de Grandlieu, Loire inférieure, in which pyroxene-plagioclase-symplectite occurs exactly in the same manner as in the Norwegian examples in its moderately advanced stages.

Laura Hezner[5] described, in great detail, the development of turbid border zones in the eclogite-pyroxenes of Sulztal and their alteration into an intergrowth of hornblende and plagioclase. It is said that the host-mineral, in the coarsest varieties, may be determined as hornblende and, concerning the finest, dusty-looking portion, it is added: "Sehr feine Stellen unterscheiden sich nach Farbe, Polarisationsfarbe und Doppelbrechung so wenig vom Omphazit, dass sie wahrscheinlich noch zu ihm gerechnet werden müssen."

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[1] Loc. cit. (T. M. P. M. 1882).

[2] P. Lohmann, Neue Beiträge zur Kenntniss des Eklogits vom mikroskopischen, mineralogischen und archäologischen Standpunkt. N. J. f. Min. etc. 1884.

[3] A. Lacroix. Etude pétrographique des eclogites de la Loire inferieure. Bull. Sci. Nat. del'Ouest de la France. 1891, I, p. 81

[4] S. Franchi, Ueber Feldspaturalitization der Natron-Thonerde-Pyroxene aus den eklogitischen Glimmerschiefern der Gebirge von Biella (Graiische Alpen). N. J. Min. etc. 1902, II, p. 112.

[5] Loc. cit. (T. M. P. M. 1903, p. 451 and 507).

The Kelyphite.

The kelyphitic mantles around the crystals of garnet, in the eclogites under consideration, invariably consist of green hornblende. Very numerous specimens do not show any kelyphite whatever, but the pyroxene meets the garnet with perfectly sharp lines. Many specimens, e. g. those of the chloromelanite-eclogite, having zones of diopside-plagioclase-symplectite in its little advanced stages, have nevertheless no kelyphite, but all those in which the symplectite has developed farther, contain kelyphite also.

The colour of the kelyphite-hornblende is intensively green, except in the segregations in olivine-rocks, in which brownish or almost colourless kelyphite was met with.

At amphibolitization the kelyphitic zones grow thicker and finally the whole crystals may have altered.

Actually this is the most essential process in the amphibolitization. Hornblende cannot originate from the garnet alone nor from the clinopyroxene alone; there must be an interaction of both. Conformably to this expectation the amphibolitization, in the eclogites, is invariably seen to take source from the kelyphite shells.

The kelyphite found in the garnet-olivine-rock from Almklovdalen, analogous to the original kelyphite of Schrauf, consists of a zone of fine fibrous brown-coloured mineral which from its extinction angles seems most like some clinoamphibole. Grains of green or brown spinel often are found all around this zone.

All the kinds of kelyphite are, from the facies theory, good indicators of the posterior facies of the rock, i.e. that facies in which the alteration has taken place. In the eclogites and dunites of Nordfjord and Møre the kelyphite, as a rule, means a first stage of amphibolitization, but in the garnet-bearing segregations in the labradorite-rock in the Bergen region we shall make acquaintance with greenschist-kelyphite, composed of chlorite and epidote-minerals.

The formation of kelyphite in garnet-olivine-rocks from Saxony, Bohemia and the Forest region of Lower Austria, studied by Mrha[1], is mainly an incipient alteration from the eclogite into the hornfels (gabbro) facies. Mrha gave an unusually correct characteristic of the nature of the alteration which may be quoted in extenso, as being no doubt one of the earliest clear applications of the static view-point in petrology.

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[1] Josef Mrha, Beiträge zur Kenntniss des Kelyphits. T. M. P. M. 19, 1900, p. 111.

After having stated that the kelyphitization, a change of pyrope and olivine into pyroxene and spinel, is accompanied by increase of the mol. volume from 275 to 312.7, Mrha continues:

"Der Granat ist als Erstarrungsprodukt flüssiger Magmen unter Atmosphärendruck nicht bekannt. Zu seiner Bildung ist daher, wie auch aus der Unmöglichkeit, ihn aus seiner Schmelze krystallisiert zu erhalten, hervorgeht, bedeutender Druck erforderlich. Der bei diesem Drucke vorhandene Gleichgewichtszustand zwischen Pyrop und Olivin wurde jedoch gestört, als das Olivinmagma, das die Pyrope enthielt, unter geringeren Druck gelangte. Das Resultat dieser Störung war die Ausbildung einer Contactzone von Mineralen mit grösseren Molecularvolumen."

Similar formation of orthopyroxene and spinel round the garnet also has taken place in the eclogite nodules in South Africa[1].

The Amphibolitization.

The occurrence of amphibolitized border-zones round eclogites enclosed in gneiss is a universal phenomenon in Norway as well as in other countries. The breadth of the altered zones, in the occurrences in Nordfjord and Møre, varies from a few centimeters to several decimeters and even metres. I have seen large masses of amphibolite which enclose cores of eclogite representing the last residues of the unaltered rock.

This phenomenon was studied microscopically in specimens from Silden in Selje, collected by Dr. H. Reusch, and in my own specimens from Bryggen.

Megascopically the amphibolitized rock differs from the unaltered eclogite by its dark colour.

A specimen from Silden, representing a little advanced stage of alteration, differs from the eclogites containing diopside-plagioclase symplectite chiefly in the farther development of the kelyphite. It shows a diopside-plagioclase-symplectite, in which the feldspar rods attain a breadth of 0,01 mm and whose structure is in all respects identical with many examples described in the previous chapter. There is no other difference than a trace of uralitization, appearing as a paramorphic change most advanced in the vicinity of the kelyphite shells. Most of the individuals of pyroxene have outer zones of amphibole, but in others the amphibole occurs as enclosed spots. The symplectic structure and the plagioclase rods remain unchanged in this alteration. As the pyroxene and hornblende are seen in homoaxial growth, both these may be easily determined from their extinction angles, the magnitude of the axial angles and the optic character (in the pyroxene $2V\gamma = 60^\circ \pm$, in the amphibole $2V\alpha = 75^\circ \pm$). The hornblende is pale green in colour. A few larger grains of pale amphibole of earlier date, probably from the last stage of consolidation, are embedded in the mass and appear entirely untouched by the changes.

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[1] Percy Wagner, op. cit. (Berlin 1909), p. 101.

The crystals of garnet are surrounded by kelyphite, composed of dark green hornblende intergrown with a few feldspar rods in a symplectic manner.

Very striking is the alteration of rutile into leucoxene-like titanite, here occurring at its first stage, as thin zones round some of the brown grains.

In another specimen we find the amphibolitization a little more developed (fig. 11, pl. II). The symplectite, with preserved structure, has been entirely uralitized. At places the symplectic structure has become a little coarser.

But little remains of the grains of garnet; the greater part has been altered into green hornblende with symplectic plagioclase and frequent octahedra of magnetite.

About a half of the rutile has been altered into leucoxene (with aggregate-polarization). Those crystals of rutile enclosed in the unaltered garnet show no change whatever.

At further stages the structure of the hornblende-plagioclase-symplectite begins to alter. The hornblende, faithful to its nature, tends to develope idioblastic prism faces and to grow in length (fig. 12, pl. II). The rod-shape of the plagioclase hereby becomes destroyed; this mineral then fills up the interstices between the hornblende prisms and soon loses its individuality. The structure becomes more and more like that of a usual granoblastic amphibolite. But the aggregates of dark green hornblende with iron ore, i. e. the kelyphite, representing the earlier garnet of which a kernel may or may not be preserved, and the parallel or subparallel groups of the hornblende prisms in the ground-mass, the substitute of the earlier diopside-plagioclase-intergrowth, remind us that we have to do with an amphibolitized eclogite.

Laura Hezner[1] distinguishes two kinds of amphibolitization of eclogites: "Typus I. Die amphibolisierung der Omphazite bleibt an feine Verfaserung geknüpft . . . Theoretisches Endglied (nur fleckweise erreicht); porphyrartiger Amphibolit mit nephritischer Grundmasse und Einsprenglingen aus rundlichen Hornblendeaggregaten . . ."

"Typus II. Die Ausfaserung der Omphazite vergröbert sich mit der Entfernung vom Pyroxenkern und geht in körnige oder leistige grüne Hornblende über . . . Theoretisches Endglied: Körniger Amphibolit . . ."

Hezner's type I is identical with what has been just described, although she has not followed its development in such a detail as I have done. As to type II, I have not observed, in the Norwegian eclogites, that common granular amphibolites have indeed developed in that way, although it is not impossible. Granular amphibolite is of common occurrence in association with the eclogites, but it seems to me more probable that it then crystallized primarily in the amphibolite facies, as we assume that partly was the case with the Romsdalshorn rock.

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[1] Loc. cit. (T. M. P. M. 22, 1903, p. 505).

The first stage of alteration of the enstatite, in the specimens rom Sulø near Aalesund, Saetre on Hareid, and Kjøde and Listø in Selje appears in the development of narrow border zones almost black from pigmentary material. Laura Hezner[1] describes quite a similar phenomenon in the eclogite-amphibolite from Sulztal and believes it to contain green hornblende. From its greenish tint the alteration product in our rocks would also seem to be hornblende.

The amphibolitization being an interaction of garnet and pyroxene, either of these, as a rule, will be exhausted first. Usually some garnet has remained. Now, the garnets rich in pyrope are not stable in the amphibolite facies, and the garnets actually preserved in garnet-amphibolites have in all cases so far studied proved to be rich in almandite, as shown later on.

It might therefore be supposed that the garnets, at the amphibolitization, should be enriched in almandite, but we have not yet any positive evidence on this point.

The amphibolitization of eclogites is a diaphtoretic metamorphism in the sense of Becke, or, in the language of the facies theory, a change from the eclogite to the amphibolite facies. The alteration apparently took place during that time when the inclusions of eclogite were submerged in the gneiss magma and the crystallization began there. The temperature had then sunk to the field of stability of the amphibolite, and the presence of mineralizers emanating from the magma favoured the re-crystallization in the outer zones of the inclusions and on the walls of joints in which solutions of silicic acid intruded, giving rise to quartz-veins.

It was not determined by means of analyses, whether any change in the bulk composition was induced by this alteration or not, but comparing the resulting amphibolites with others whose composition is known, no change would seem probable, as a rule.[2] But in some cases a considerable addition of material is apparent. In the altered zones around the quartz veins on Silden (p. 37) the amphibolite contains very much biotite. In many other cases the amount of plagioclase is larger than what could originate from the eclogite minerals. And true resorption and assimilation also has taken place, often perhaps not much, but in other cases on a large scale.

Sometimes zoisite, epidote, margarite, and chlorite appear in the eclogites, indicating that alteration has surpassed the amphibolite facies and approached the greenschist facies. Although this is no rare case and the re-crystallization of such hydrated minerals may be quantitatively considerable, they appear, however, distinctly apart from the amphibolitization.

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[1] Loc. cit. (T. M. P. M. 22, 1903, p. 510).

[2] When this paper was already sent to the print, I received the work of M^{lle} Y. Brière, "Les eclogites françaises — leur composition minéralogique et chimique; leur origine", thesis, Paris 1920. Among many other interesting results this careful study contains analytical evidence, in the case of an eclogite and its amphibolitic alteration product from Puy Ferrières, that no change of the bulk composition has taken place (op. cit. p. 55).

The most conspicuous alteration of the eclogites in Nordfjord and Møre is that into the amphibolite facies. At its first stage its pyroxene is recrystallized, in a curious way, every grain eating itself into some of its neighbours and at the same time separating out plagioclase in symplectitic intergrowth with the pyroxene. Chemically this change probably means a breaking up of the aluminous pyroxenes, containing jadeite and lime-jadeite, into diopside and soda-lime feldspar.

Another alteration is the growth of green hornblende as shells around the garnet and at its expense, the kelyphite. This zone may grow thicker and spread out into the pyroxene mass.

At a final stage all the diopside of the diopside-plagioclase-symplectite is uralitized with preserved structure which, however, will gradually alter, the hornblende tending to develop a prismatic habit and the plagioclase to be granulated. The end product is a granular amphibolite, with or without garnet, in which groups of parallel short prisms of hornblende are the only reminiscence from its earlier pyroxene and aggregations of green hornblende, often with magnetite, from its garnet.

There is practically no doubt that this is the same process as that formerly described by Lacroix, Laura Hezner, S. Franchi (feldspar-uralitization) and others, but the earlier investigators have not followed it through its different stages, viz. the formation of diopside-plagioclase-symplectite, the kelyphitization and the uralitization, nor have they recognized the mutual relations or the petrological importance of these processes.

Change of Facies during Crystallization.

Amphibole-eclogite.

Among the eclogite minerals we have repeatedly mentioned the occurrence of pale green hornblende that is primary, although it has originated at the expense of the two chief eclogite constituents and apparently did not belong to the equilibrium together with them. By exhaustion of the pyroxene, amphibole-eclogites may result.

Such rocks have changed facies during their crystallization. I have not observed gradual transitions from such amphibole-eclogites into true amphibolites, and it seems as though the former would belong to an independent facies, closest related to the eclogite facies. The appearance of such amphibole probably depends upon a fall of the temperature, and a reduction of pressure is perhaps not at all necessary.

Eclogite-hornblendegabbro.

Of quite another character is the development of the minerals of the hornblende-gabbro facies at the last phase of the consolidation of eclogites. As an example of it, we have given a quantitative investigation of the eclogite-hornblende-gabbro of Romsdalshorn (p. 43) and here will be mentioned a few other examples of this very common phenomenon.

As the transition into the new facies usually takes place when much garnet has already crystallized out, the rest-magma is then enriched in lime, and diopside separates out along with hornblende and plagioclase. A characteristic example was a specimen from Vaagsø, Nordfjord, where the eclogite-pyroxene had altered into the diopside-plagioclase-symplectite, and a granular mass of brown hornblende and plagioclase fills up the interstices of the older minerals.

A specimen from Rofjeldets Hammere, Nordmøre, on the other hand, represents a case where the residual magma had excessive magnesia and a bulk composition somewhat various from that of the ordinary eclogites. Here the diopside-plagioclase-symplectite is present as elongated grains, and between them are vein-shaped strings of oligoclase, green hornblende and biotite.

A specimen from Brandsaeter, Kornstadfjord, Nordmøre, shows well developed eclogite minerals and between them a granular aggregate of brown hornblende and plagioclase (fig. 13, pl. III).

The change of facies also may result in a rock quite devoid of pyroxene. An example of this is a specimen from Vik, Gurskø, Søndmøre, containing garnet, greenish brown hornblende and bytownite.

A specimen from Halsnes, Tusteren, Nordmøre, is similar with the Romsdalshorn rock. This contains large rounded crystals of garnet and clinopyroxene, the latter in part altered into diopside-plagioclase-symplectite, both embedded in still larger indivivuals of plagioclase in which also are smaller grains of brown hornblende and biotite, in part filling up the interstices between the older minerals.

In this connection I shall still give a note of some rocks from Hanedalstind, of which Professor V. M. Goldschmidt kindly lent me four thin sections. Their crystallization has begun in the eclogite facies, and one of them is composed of garnet and diopside-plagioclase-symplectite, whose interstices are filled up with green hornblende. Another thin section shows the same symplectite as large grains in a ground-mass of brown hornblende, biotite and plagioclase, and, instead of garnet, large groups of green hornblende and magnetite. The plagioclase (andesine) is too abundant for an earlier eclogite.

Still another slice shows the symplectite in a partly uralitized state, embedded in large individuals of plagioclase and a hornblende-plagioclase-mass, and finally, the most perfect state of amphibolitization is represented by a thin section, which contains only hornblende-plagioclase-symplectite in which the new development of the prism shapes in the symplectic hornblende is notable.

In the previous discussion I have regarded the structural evidence as sufficient to decide whether an eclogite has undergone a posterior alteration into the amphibolite facies or has been brought under the conditions of the latter before perfect consolidation, and I believe the evidence to be convincing for the former alternativ, when symplectites occur, and for the latter, when brown hornblende filling the interstices, or large and anhedral individuals of plagioclase as a mesostasis, are present. But a granular hornblende-plagioclase-mass might also be taken for metamorphic, and it may be difficult to know exactly the mode of origin.

Professor V. M. Goldschmidt privately suggested the following reasoning: If an eclogite-mass has undergone a posterior change, this will have worked inward from the border and we shall find the border-zones most altered, while the opposite will be the case, if a change of facies has happened during the crystallization, as the inner parts of a magma mass must have consolidated last and at lowest temperatures.

From my field experience I know only the case of alteration of the border-zones and have not studied in the field those occurrences whose structures point to a change of facies. Concerning the Romsdalshorn eclogite-hornblende-gabbro, Th. Kjerulf[1] states that its border-zones are amphibolitic. The occurrence of alteration at the borders, of course, would not controvert a change of facies in the midst the mass.

The change of facies may occur before the final consolidation, but there is another possibility, that the change of conditions might cause a perfect or partial refusion of the eclogite. Under certain conditions this must necessarily happen on the reduction of pressure, in consequence of the large difference of volume between the eclogite and its magma. Refusion is the more likely, the larger the mass of eclogite.

On the Age of the Gneiss Formation of Nordfjord and Møre.

The problem concerning the geological age of the gneiss formation under consideration does not belong to the subject of the present treatise. Here we want only to state that its age is still unknown.

Two different suppositions may possibly be considered: (I) That the gneiss of Nordfjord and Møre is Archaean or (2) that it belongs to the Caledonian eruptives.

Whatever may be the age of these rocks, the labradorite-rocks, eclogites and the olivine-rocks belong to the same age-complex as the gneiss.

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[1] Loc. cit.

Now, this very rare combinations of igneous rocks has also been met with in the Bergen region, and are there known to be Caledonian. It might be regarded as a strange coincidence if the very analogous formation a little farther North were of another age and thus geologically independent of the Bergen igneous complex. No great bearing, however, can be assigned to such a petrological analogy when geological age is being considered.

The monometamorphic character of the gneiss-formation and its whole series of structural varieties indicating that it has been, during its consolidation and shortly after, subjected to an extremely intense stress whose direction, as a whole, is conformable to the strike of the Caledonian zone, would also seem to favour the supposition of a Caledonian age.

As to the general conclusions which may be drawn from the facts here discussed it is of no consequence, whether the formation has originated in pre-Cambrian or in later times. In any case, however, we must assume that the eclogite-bearing gneiss formation, as a half-consolidated mass, had been brought up from great depths in connection with a great diastrophism and then had been brought near the earth's surface by a quick denudation, or else no eclogites would have been spared from amphibolitization.

GARNET IN THE LABRADORITE-ROCK OF THE SOGN AREA.

Inclusions of Olivine-rock in Labradorite-rock near Aurlandsfjord in Indre Sogn.

In 1917 Professor Goldschmidt collected, from the East side of Aurlandsfjord in Indre Sogn, South of Sognefjord, large blocks of labradorite-rock containing dark inclusions. The outer zones of these inclusions being garnet-bearing it was to be expected that their investigation would throw some light on the eclogite problem, and Professor Goldschmidt with great courtesy lent me the specimens for study.

The appearance of one of these large specimens is seen in fig. 11, while the distribution of the minerals is schematically shown in fig. 12.

The unaltered labradorite-rock in Sogn, according to V. M. Goldschmidt[1], generally consists mainly of a plagioclase about Ab_{40} and still more anorthitic. At the immediate contact with the inclusions, however, the plagioclase contains 60 pt albite and, in the border-zones, still more, showing a zonal structure. Maximum extinction angles in sections $\perp$ PM are 20°. Thus the inclusions are surrounded by a more albitic zone which, megascopically, appears by its lighter colour. This zone is a few centimeters thick. Besides the plagioclase, the labradorite-rock contains but trifling amounts of other minerals. Near the contact there may be seen some prisms of green hornblende and anthophyllite (α = yellowish, β = greyish green, γ = greyish blue; $\gamma > \beta > \alpha$; $2V\gamma$ = about 60°), and more generally, though very sparingly, hypersthene. Euhedral crystals of garnet are scattered sparingly in the vicinity of the inclusions and elsewhere, being of general occurrence in the Sogn labradorite-rocks, as described by J. Rekstad.[1]

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[1] V. M. Goldschmidt, Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegens, IV, Übersicht der Eruptivgesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem. Vid.-Selsk. Skrifter. I. Mat.-Naturv. Kl. 1916, N:o 2, p. 31.

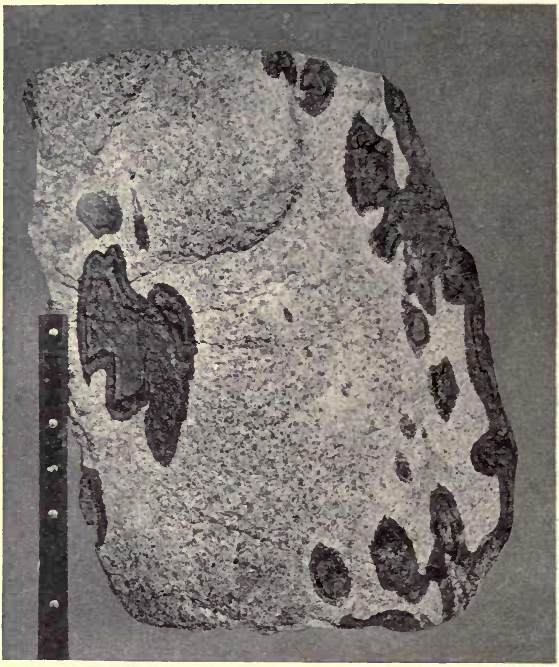

Fig. 11. Inclusions of olivine-rock in labradorite-rock. Aurlandsfjord, Sogn. (The ruler serving as a scale is 20 cm. long.)

The rock also contains occasional grains of zoisite and green biotite. The former of these occur, in a peculiar manner, in the midst of small patches in wich the feldspar has been finely granulated. Granulation also is common at the boundaries of the feldspar crystals (mortar-structure). The rock exhibits much mechanical deformation, a common phenomenon in the Sogn labradorite-rocks (cf. J. Rekstad and V. M. Goldschmidt, op. cit.).

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[1] J. Rekstad, Fra Indre Sogn. Norges geol. Unders. Aarbog 1907, 7, p. 28.
J. Rekstad, Geologiske iagttagelser fra strøket mellem Sognefjord, Eksingedal og Vossestranden. Ibid. 1903, 1, p. 6, fig. 2.

The inner portions of the inclusions consist almost exclusively of olivine as a millimeter-grained mass. Cracks in the crystals are filled up with pigmentary black substance together with some brown serpentine. In making separation with a heavy solution this dark substance was concentrated in portions less heavy than the clean olivine. By a chemical test the mineral was found to be serpentine mixed with iron ore.

The specific gravity of the olivine was found to be 3.54, which should, according to a graphical interpolation from known values, correspond to about 22 $^0/_0$ FeO. The optic axial angle is so near 90° that the optic character only with difficulty can be determined as negative. This also conforms to a composition with about 22 $^0/_0$ FeO or $\mathrm{Fa}_{24}\mathrm{Fo}_{76}$. $\beta = 1.705 \pm 0.001$, from which results the composition $\mathrm{Fa}_{25}\mathrm{Fo}_{75}$.

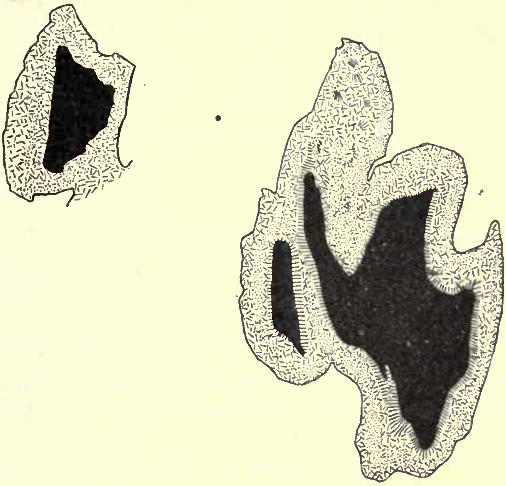

Fig. 12. Schematical view of the inclusions. Black is olivine, surrounded by successive zones of anthophyllite and hornblende with garnet (dotted).

The olivine-rock is surrounded by successive zones of anthophyllite which, in the inner zone, is a fibrous, asbestos-like variety and, contrary to the anthophyllite in the labradorite-rock, colourless in thin section. Its fibres are always arranged perpendicular to the zones. I determined $\gamma = 1.645 \pm 0.002$. If this is a non-aluminous anthophyllite, as would seem probable from its large positive acute axial angle, its composition might be interpolated from the values in the anthophyllites from Franklin and Kongsberg (Rosenbusch-Wülfing, Mikr.Phys. 1, 2, p. 153) at about 12 $^0/_0$ FeO and 27 $^0/_0$ MgO.

The hypersthene occurs in the form of equidimensional grains and shows a distinct red and green pleochroism. The optic character is negative and the axial angle about 80°. Hence it should contain about 25 mol. % $FeSiO_3$.

In the garnet-bearing zones the garnet occurs as rounded crystals about 0.5 cm in diameter, and their interstices are filled up with finely granular hornblende. The garnet was separated and analyzed by the writer with the following result:

	%	Mol. numb.
SiO_2	40.17	668
Al_2O_3	22.07	217
Fe_2O_3	1.19	8
FeO	17.26	240
MnO	0.55	8
MgO	11.61	290
CaO	6.82	121
TiO_2	tr.	
	99.67	

Sp. g. = 3.83.

$n_D = 1.7658.$

$RO : R_2O_3 : SiO_2 = 2.93 : 1 : 2.97.$

Composition: $(Fe_{37}Mn_1Mg_{44}Ca_{18})_3(Al_{94}Fe_6)_2.$

The sample was very free from any alien substances. We meet here with a garnet in which ferrous oxide and magnesia are almost equal in quantity.

The hornblende is a green variety of medium intensity of the colours sharing all the properties of common hornblende. Its mean index of refraction was found to be $\beta = 1.655 \pm 0.002$. Towards the labradorite-rock the hornblende protrudes as fairly euhedral prisms, showing well-developed terminal faces.

In those zones free from garnet the hornblende frequently assumes a somewhat coarser grain. Grains of dark green spinel surrounded by a zone of plagioclase are seen in the hornblende mass. This plagioclase seems, from its refringence, to be at least as anorthitic as that in the neighbouring rock.

This garnet-bearing zone appears as a reaction zone between the olivine and the labradorite, and in fact we could call it with Sederholm a reaction-equation written in rock. Moreover, the petrologist sees here an equation that he knows very well, for F. Becke long ago wrote it as an example of interaction between minerals during rock metamorphism, whereby the product acquires a considerably smaller molecular volume than the earlier combination:

$$CaAl_2Si_2O_8 + Mg_2SiO_4 = Mg_2CaAl_2Si_3O_{12}.$$
$$\text{Anorthite} + \text{olivine} = \text{garnet.}$$

Though it is quite possible that garnets having strictly the composition postulated by this equation may exist in some eclogites, this is, however, not the case here, as our garnet contains much less lime. The reaction actually was more complicated.

The inclusions of olivine-rock must be regarded as primary early segregations from the magma, and the boundary zones were formed probably before the labradorite-rock was solidified. This presumption is closest at hand, and nothing points to the contrary. The occurrence of the same kind of garnet as primary crystals in the unaltered labradorite-rock proves that the conditions of existence of garnet were already present at the magmatic stage.

The hornblende, on the other hand, is clearly posterior to the garnet, though it may possibly have crystallized earlier than the labradorite. It is much of the same nature as the kelyphite zones in many eclogites, and the occurrence of spinel also conforms to this view.

Garnet in Labradorite-rock in Indre Sogn.

As already pointed out, the Sogn labradorite-rocks often contain garnet. There are two modes of occurrence of this mineral: either in dark segregations together with other mafic minerals, and as single idiomorphic crystals. Both these kinds are represented in the upper part of Krokedalen, where, according to J. Rekstad[1], "the rock consists of reddish violet labradorite with frequent lenses and layer-shaped masses of green colour. The rock contains, in the light feldspar portions as well as in the dark hornblende portions, considerable amounts of garnet".

I have had thin sections made of several specimens of both kinds kept in the Museum in Christiania and will briefly describe a few examples.

A specimen of "eclogite" from Fodnes, Laerdalsfjord, collected by Th. Kjerulf, represents the dark inclusions (fig. 13). It is a medium-grained and foliated rock in which quite small lenticular veinlets of feldspar are visible to the naked eye. It is composed of hypersthene, garnet and plagioclase besides much iron ore and a little brown hornblende.

The crystals of hypersthene are surrounded by granulated zones of the same mineral, and where several crystals have been aggregated together, there the structure is mortar-like. The crystals of garnet, on the other hand, are rounded as though corroded and always surrounded by zones of granular feldspar with iron ore. This feldspar is pure plagioclase, while the feldspar in the small veinlets is antiperthite.

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[1] Op. cit. (N. G. U. Aarbog 1907, VII) p. 28.

Another specimen from Okken, collected by Th. Kjerulf and Krohn, exhibits a coarsely granular rock in which about a half of the mass is feldspar and the other half garnet, hypersthene and hornblende, all approximately in equal amounts, and very little black pigment-like iron ore in all the mafic minerals.

I determined the refringence of this garnet, obtaining

$$n_D = 1.7571.$$

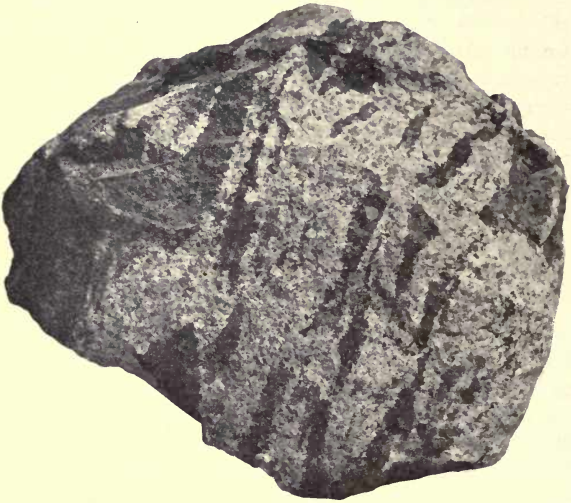

Fig. 13. Dark inclusions in labradorite-rock. Fodnaes, Laerdalsfjord. 1/2 of the natural size.

Hence the probable composition should be $Fe_{34}Mg_{48}Ca_{18}$, or this garnet should contain still larger amounts of the magnesia compound than the garnet from Aurlandsfjord.

The hornblende is very pale green, the hypersthene shows faint pleochroism. Their axial angles are of the same order of magnitude as in these minerals in the inclusions near Aurlandsfjord.

The plagioclase is about Ab_{25} or Ab_{35}, showing, in sections $\perp$ PM extinction angles of 37°.

In this plagioclase I noticed a special kind of zonal development which seems to deserve some description: at its borders towards the hornblende there are zones of more sodic mixtures, but not where it meets other minerals. This accords with the general rule that the formation of hornblende takes place at the expense of the anorthite.

A specimen from Naerødal, collected by Th. Kjerulf, exhibits a labradorite rock containing numerous almost plate-formed dark inclusions, much elongated in one direction and measuring as much as 2 cm in thickness. They have border zones mainly composed of garnet as rounded crystals whose interstices are filled up with pale green hornblende. These zones measure 8 mm in maximum. Their thickness does not stand in any relation to the thickness of the inner zone and they are sometimes absent. The inner parts consist of clinopyroxene of a pale violet colour. Thus these inclusions, though in their outer zone much resembling the inclusions at Aurlandsfjord, have quite another composition.

Quite the same characters were observed in plate-shaped inclusions in labradorite-rock from Brandsaetstølen, Vossestranden. The inner kernels contain brown hornblende, besides monoclinic pyroxene. As in the former examples, the plagioclase in the close vicinity of the inclusions is more sodic than the average labradorite, here containing but 40 per cent An.

Brownish green hornblende besides garnet, hypersthene and diopsidic pyroxene form similar inclusions in the labradorite-rock near Langenesbaekken, Eidsfjord, from which locality specimens have been collected by V. M. Goldschmidt. Here the hornblende fills up the interstices between the other minerals which are all rounded in shape.

At the same locality, the main labradorite-rock is garnet-bearing. The crystals, with sharp boundaries, though rounded forms, are arranged in parallel rows and with the garnet are associated grains of colourless monoclinic pyroxene and brownish green hornblende.

In the specimens from Langenesbaekken, as well, the plagioclase in the vicinity of the inclusions is more sodic than in the average labradorite-rock.

Garnet-gabbro from Aardal, Sogn.

A specimen of garnet-gabbro from the Tya transport way, Aardal, Sogn, collected in 1917 by Mrs. M. Johnson-Høst, was analyzed by the writer with the following result:

	%	Mol. numb.	Mol. %	Norm	
SiO_2	48.98	816	52.68	Orthoclase	7.78
Al_2O_3	15.91	156	10.07	Albite	23.58
Fe_2O_3	1.34	8	10.97	Anorthite	26.97
FeO	10.83	151		Σ sal =	58.33
MnO	0.20	3		Diopside	13.11
MgO	6.74	169	10.91	Hypersthene	7.76
CaO	9.00	161	10.39	Olivine	14.47
Na_2O	2.79	45	2.91	Apatite	0.67
K_2O	1.34	14	0.90	Magnetite	1.86
TiO_2	1.40	18	1.17	Ilmenite	2.74
P_2O_5	0.35	2	—		
H_2O	0.35	—	—	Σ fem =	40.61
	99.28		100.00		98.94

Sp. g. = 3.12 (t = 12° C).

Auvergnose, III, 5, 4, 3.

This is a very typical and common gabbroid composition. The Aardal rock belongs to that division of the Caledonian eruptives by V. M. Goldschmidt called the Bergen Jotun stem (Stamm)[1]. An important part of these rocks, the so-called Jotun norites, are characterized by a high proportion of potash, the composition in other respects being noritic. This characteristic is not very pronounced in the rock under consideration, nor does it contain perthitic feldspar, so typical of the Jotun norites, and it may be therefore classed with the normal-gabbroid branch of this "stem". To show the close similarity with another member of the same branch, we will quote the analysis made by M. Dittrich of saussurite-amphibolite, a metamorphic derivative of a normal-gabbroid Jotun rock without garnet from Framnaes, South and of Tyin lake, Jotunheimen (Goldschmidt op, cit. p. 28), I.

Analysis II made by M. Dittrich (op. cit. p. 38) is one of typical jotun norite from Breikvamsnaase, Jotunheimen. III is the garnet-gabbro from Aardal.

The most abundant mineral of the garnet-gabbro is plagioclase and second in abundance is the garnet. Thereafter follow clinopyroxene, biotite, hornblende, hypersthene and titaniferous iron ore.

The composition of the plagioclase conforms to Ab_{70}, showing in sections $\perp$ PM $\gamma' : M = 11°$. This angle was measured in numerous crystals and there seems not to exist any zonal development or other kinds of heterogeneity.

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[1] Op. cit. (Vid.-Selsk. Skrifter. I. Mat.-Naturv. Kl. 1916. N:o 2).

	I.	II.	III.
SiO_2	47.62	52.76	48.98
Al_2O_3	15.54	15.40	15.91
Cr_2O_3	tr.	tr.	—
Fe_2O_3	1.72	4.55	1.34
FeO	11.44	6.59	10.88
MnO	0.19	0.14	0.20
MgO	6.20	6.10	6.74
CaO	7.68	7.69	9.00
Na_2O	3.09	3.36	2.79
K_2O	1.54	2.02	1.34
TiO_2	1.00	0.52	1.40
P_2O_5	0.19	0.29	0.35
CO_2	0.15	0.38	—
H_2O	3.23	0.46	0.35
	99.79	100.26	99.28

The garnet occurs as rounded crystals. I separated a sample of it with Clerici's solution, and a chemical analysis of the garnet was executed by Mr. L. Thomassen with the following result.

	$^0/_0$	Mol. numb.
SiO_2	38.44	641
Al_2O_3	22.73	223
Fe_2O_3	2.36	15
FeO	23.00	319
MnO	0.60	8
MgO	7.89	197
CaO	4.82	86
TiO_2	0.21	—
H_2O	0.22	—
	100.27	

Sp.g. = 3.917

$n_D = 1.7887$

$RO : R_2O_3 : SiO_2 = 2.56 : 1 : 2.70$

Composition: $(Fe_{52}Mn_1Mg_{33}Ca_{14})_3(Al_{94}Fe_6)_2$.

We find the garnet to be much richer in iron in proportion to magnesia than are the other mafic constituents, the ratio MgO : FeO being, in the garnet, 1 : 0.63 while in the rock it is 1 : 0.89. Thus the pyroxene must be poor in iron.

The clinopyroxene is almost colourless or faintly greenish grey. Diallage-parting after (100) is prominent. $2E = 88^\circ$, measured with Klein's lens. Assuming $\beta = 1.70$, this value gives $2V = 48^\circ$. Axial dispersion is hardly noticeable.

The reddish brown biotite and, in smaller quantities, the green hornblende occur only as groups of fringes and minute grains around the garnet and pyroxene. The iron ore is more independent, but its grains show irregular shapes.

Occasional grains of orthorhombic pyroxene are associated with the monoclinic pyroxene.

The rounded garnets often are enclosed in the pyroxene, thus having the appearance of that mineral earliest crystallized out. They are free from inclusions.

All the minerals display signs of strong mechanical deformation. The plagioclase for the greater part has been granulated, and the central kernels of the crystals still preserved show bent lamellae and undulatory extinction. As Goldschmidt already pointed out, (op. cit.) these phenomena, in the Jotun rocks, are probably of a protoclastic character.

The garnet-gabbro from Aardal is genetically related to the eclogite-gabbro from Romsdalshorn. Here also different stages of mineral development may be discerned. The prevalence of iron over magnesia was favourable to the preservation of the garnet, and therefore we do not see here any proofs of the garnet having become unstable, although it no doubt at first crystallized in the eclogite facies.

The garnet-bearing variety, according to private information by Prof. Goldschmidt, occurs as a boundary variety in a gabbro mass.

ECLOGITE AND GARNET IN THE LABRADORITE-ROCKS OF THE BERGEN REGION.

Synopsis of the Labradorite-rock Series after C. F. Kolderup.

The labradorite-rocks in the Bergen region were first dealt with by C. F. Naumann[1] and later by Th. Hiortdahl and M. Irgens[2] who already characterized the eclogite occurring in connection with these rocks simply as "a variety of the labradorite-rock, and no independent rock".

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[1] C. F. Naumann, Beiträge zur Kenntniss Norwegens, Leipzig 1824.

[2] Th. Hiortdahl og M. Irgens, Geologiske Undersøgelser i Bergens Omegn. Universitets-program før andet halvaar 1862.

In a monographical treatise C. F. Kolderup[1] described this rock-series in detail and cleared up the genetic relations. I take the liberty of abstracting, from this memoir, some facts having special interest for our study.

The primary minerals of the labradorite-rock are plagioclase, garnet, pyroxene, biotite, ilmenite, magnetite, apatite and pyrite, and the secondary are rutile, hornblende, chlorite, muscovite and paragonite, epidote, zoisite, albite and quartz. Garnet and biotite are also found as secondary products, but the occurrence of primary garnet is regarded as an indubitable fact and as being of great importance: "Dieser Umstand, die Granate als primär aufzufassen, ist für die ganze Auffassung der Eruption der Labradorfelse von grosser Bedeutung." (Op. cit. p. 19.)

The plagioclase has the average composition Ab_1An_2 which is also the average of all the analyzed rock-making labradorites in Norway.

The garnet is, in the Bergen labradorite-rocks, of universal occurrence, partly evenly distributed and partly aggregated in dark lenticular masses in which they either form a peripheral zone or a kernel. The garnet is always isotropic. Its grains are surrounded by kelyphitic zones of green hornblende.

An analysis of garnet from labradorite-rock near Alvaerstrommen (p. 32) may be quoted (the mol. numbers calculated by the present writer).

	0/0	Mol. number
SiO_2	42.21	703
Al_2O_3	13.55	133
Fe_2O_3	12.91	81
FeO	15.32	215
MnO	tr.	
MgO	8.91	223
CaO	6.91	123
Na_2O	0.21	—
	100.22	

$RO : R_2O_3 : SiO_2 = 2.62 : 1 : 3.29$

Composition: $(Fe_{38}Mg_{40}Ca_{22})_3(Al_{62}Fe_{38})$.

Clinopyroxene is often abundant. An analysis of diallage from labradorite-rock near Alvaerstrommen shows the following composition (p. 28):

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[1] Carl Fred. Kolderup, Die Labradorfelse des westlichen Norwegens. II. Die Labradorfelse und die mit denselben verwandten Gesteine in dem Bergensgebiete. Bergens Museums Aarbog 1903, N:o 12.

	%	Mol. number
SiO_2	48.11	797
TiO_2	0.97	12
Al_2O_3	7.55	74
Fe_2O_3	8.18	51
FeO	5.38	75
MgO	12.97	321
CaO	15.10	270
Na_2O	1.60	26
K_2O	0.30	3
	100.14	

The most peculiar characteristic of this pyroxene is its high content of alumina[1].

Following two analyses of garnet- and pyroxene-bearing labradorite-rocks (p. 36) may here be reprinted. I Sebø, Radø (by Lillejord) II Elsfjord, Holsenø (Hiortdahl and Irgens, op. cit. p. 21).

	I	II
SiO_2	49.68 %	50.01
TiO_2	0.23	—
Al_2O_3	20.86	18.95
Fe_2O_3	1.02	—
FeO	5.52	9.57
MgO	6.50	5.60
CaO	10.77	10.44
Na_2O	3.46	4.66
K_2O	1.38	2.37
H_2O	0.53	0.39
P_2O_5	0.00	—
S	0.26	—
	100.21	101.99

The segregations of the dark minerals usually have lenticular shapes, though irregular forms also occur. The lenticular structure is thought to be a consequence of stress immediately before and during the consolidation. Zonal arrangement sometimes occurs, the garnet forming the outer zone around kernels mainly composed of the clinopyroxene. This arrangement, however, is not common. (As we have seen, it is the regular case in the labradorite-rocks in Sogn). More often garnet and pyroxene have been concentrated together. — The rocks are often protoclastic and, also, kataclastic. Saussuritization of the plagioclase and a uralitization of the pyroxene are common. In the sequence of crystallization the place of the garnet is not quite clear. It seems often to have separated out earlier than the pyroxene and plagioclase, but probably it continued to crystallize contemporaneously with the others.

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[1] Hiortdahl and Irgens, op. cit. p. 23, quote an imperfect analysis of diallage from coarse-grained saussurite-gabbro, showing 49.52 SiO_2, 9.40 Al_2O_3, 10.70 Fe_2O_3 and 13.22 CaO.

The pyroxenitic segregations are not always the same in composition. Sometimes diallage is the only mineral, in other cases garnet is abundant. Often the pyroxene has altered into hornblende. Sometimes (e. g. at Alvaerstrømmen) the hornblende is brown, being probably of primary origin. Some other segregations are composed of ilmenite, pale green hornblende, biotite, garnet and feldspar (Isdalstrøm S. of Alvaerstrommen). A dark lens in labradorite-rock near Stenestø was found to be composed of garnet crystals in a mass of pale hornblende, similar to that forming the kelyphitic zones.

A special kind of segregations are those of ilmenite-pyroxenites, ilmenite-norites etc. They may contain spinel.

The eclogites occur in such a relation to the labradorite-rocks that they must be regarded as genetically connected with them. "Sie sind häufig Grenzfaziesbildungen der Labradorfelse, können auch in den centraleren Partien auftreten und kommen gleichfalls stellenweise als lagerförmige oder linsenförmige Gesteinsmassen in den sie umgebenden Gneissen vor" (p. 70). Kolderup remarks that these eclogites thus are not "Lagergesteine" in the sense of Rosenbusch's definition of that rock. "Den jetzigen Untersuchungen zu Folge bilden die Eklogite, die in oder neben den Labradorfelsen auftreten, mit diesen ein genetisches Ganze . . .". This interpretation conforms well, as Kolderup remarks, to that of Hiortdahl and Irgens.

". . . Die Structur (des Eklogites) ist fast überall die eugranitisch körnige, selbst wenn die Nebengesteine mit ausgeprägter Parallelstruktur auftreten. Als Hauptgemengteile sind Pyroxen, Hornblende und Granat vorhanden. Nebst ihnen kommen als unwesentliche Mineralien Biotit, Rutil, Eisenerze und Apatit vor; während Muscovit, Plagioklas, Zoisit, Epidot und Eisenkies als accessorische Bestandteile zu betrachten sind."

The pyroxene is said to have the characters of omphacite.

"Wo die Omphacite als grössere Körner vorhanden sind, findet man, dass sie an den Rändern von einem Gürtel faseriger Massen umgeben sind. Diese massen — haben ungefähr dieselbe Farbe wie das Hauptmineral." This change is, no doubt, identical with the formation of diopside-plagioclase-symplectite (cf. p. 70).

On p. 72 is given an analysis of eclogite from Landsvik on Holsenø, composed of omphacite, glaucophane-like hornblende (said to be no glaucophane) garnet, with a little biotite, rutile, iron ores, apatite and zoisite.

SiO_2	46.97 %
TiO_2	1.48
Al_2O_3	9.99
Fe_2O_3	0.97
FeO	10.54
MgO	11.54
CaO	14.46
Na_2O	3.17
K_2O	0.28
P_2O_5	0.20
S	0.71
	100.31

Kolderup remarks that this analysis differs from those of most other eclogites in being low in Al_2O_3 and rich in CaO and Na_2O. It is, however, a truly gabbroid composition. Placing analyses of a normal labradorite-rock, a pyroxene- and garnet-bearing labradorite-rock and this eclogite along side they appear to form a continuous series, in which the percentages of SiO_2, Al_2O_3, Fe_2O_3 and Na_2O sink while those of FeO, MgO and CaO rise.

Several occurrences of serpentine are then described in great detail (p. 74—85). Only a few features, highly interesting for us, will be quoted here.

"Die Serpentine treten in verschiedenartiger Weise auf. So findet man den Serpentin als selbständige Bildung mitten im Labradorfelsgebiete, von dem er sich durch scharfe Grenzen unterscheidet; er tritt auch als Grenzfáciesbildung des Labradorfelses und des Saussuritgabbros auf und bildet Intrusivmassen sowohl in den Gneissgesteinen als auch in den sicher silurischen Bergensschiefern."

An analysis of serpentine from Rødholmen in Lindaas shows 38.21 SiO_2, 3.25 Al_2O_3, 3.56 Fe_2O_8, 4.66 FeO, 37.60 MgO, 0.00 CaO, 1.40 Na_2O, 11.75 H_2O, sum 100.43.

Some serpentines contain remains of pyroxenes and are thought to have been derived from pyroxenites, while others contain some unaltered olivine, being changed peridotites.

Interesting for us is also the fact that many occurrences of serpentine, are situated near those of eclogites, e. g. near Landsvik on Holsenø and Arnevaagen near Bergen.

Still many other kinds of igneous rocks belong to the same differentiation series, such as norites, olivine-gabbros, mangerites, acid syenites and granites. The eclogite is considered by Kolderup as a member of the series between labradorite-rock and pyroxenites.

In another work[1] Kolderup gives a description of the Storenuten labradorite field east of Bergen. Here also garnet-bearing varieties and basic segregations occur. Special attention is given to a segregation from Hagasaeter (p. 159), mainly composed of green clinopyroxene with green hornblende, ore and garnet. In this mass are stained round aggregates of plagioclase with a kernel of a larger garnet crystal or with a boundary row of small garnet grains.

Another type from Nordviksaeteren contains numerous irregular grains of garnet embedded in a feldspar mass.

Hiortdahl and Irgens (op. cit.) designated almost all pyroxene- and garnet-bearing inclusions in the labradorite-rocks as eclogites, while Kolderup made the definition of eclogite more restricted, so as to comprise only somewhat homogeneous segregations in which the pyroxene has the omphacite-character, being clear and free from pigment and without the diallage-parting. He admits, however, that the pyroxene-garnet segregations are transitional on the way to the formation of eclogite.

The Author's Observations on Garnet-labradorite-rock in the Bergen Region.

Scapolite-bearing Garnet-labradorite-rock.

The treatise of Kolderup having been abstracted at some length my own microscopic observations can be quoted in so much fewer words. I had at my disposition the specimens collected by Th. Hiortdahl and M. Irgens in 1861, and some specimens collected by H. Reusch in 1887, and a collection of C. F. Kolderup, all kept at the Geological Museum in Christiania. Fig. 14 shows the appearance of a garnet-bearing labradorite-rock and a dark inclusion in labradorite-rock from the Bergen-region.

In the unaltered labradorite-rock the garnet appears with sharp boundary-lines and in euhedral or rounded shapes. I studied such examples from Alvaerstrommen and from Rado. Both these examples happen to contain scapolite[2].

In the specimen from Rado the scapolite occurs perfectly in the manner of a truly primary constituent, with irregular or rounded form, often enclosed in the labradorite. It is a wernerite, having $\omega - \varepsilon = 0.025$ appr., and a refringence considerably higher than that in the labradorite. Uniaxial and negative character and a tetragonal prismatic cleavage are conclusive diagnostics.

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[1] Carl Fred. Kolderup, Fjeldbygningen i strøket mellem Sørfjorden og Samnangerfjorden i Bergensfeltet. Bergens Museums Aarbog 1914. — 15, n:o 8.

[2] According to private information by professor V. M. Goldschmidt scapolite, in the labradorite-rocks of western Norway, was first observed by Professor B. Popoff.

The plagioclase in this rock shows ⊥ PM extinction angles of 22° corresponding to Ab_{60}.

Other constituents are garnet and clinopyroxene, the latter turbid from pigmentary substances and pale violet in colour, but it does not show any notable axial dispersion. It is surrounded by narrow zones of radiating fibrous hornblende, pale green in colour. The garnet locally has similar though much narrower border-zones (kelyphite).

Another specimen from Radø is a gabbro, also containing scapolite. Garnet occurs here as large crystals including rounded grains of intensely green though non-pleochroic augite which is also abundant as a coarse-grained mass with the plagioclase. The pyroxene is surrounded by zones of homoaxial hornblende. When bordering against the plagioclase that is an andesine (Ab_{65}), much saussuritized, the hornblende is surrounded by zones of epidote in myrmekite-like intergrowth with a colourless mineral which I did not succeed in determining. It is not in parallel orientation with the adjacent plagioclase and has a considerably lower refraction than the latter. From these facts and from analogy to the quartz-epidote-myrmekite formerly observed by me in the rocks from Sviatoy Noss in Transbaikalia[1] I would suppose it to be quartz.

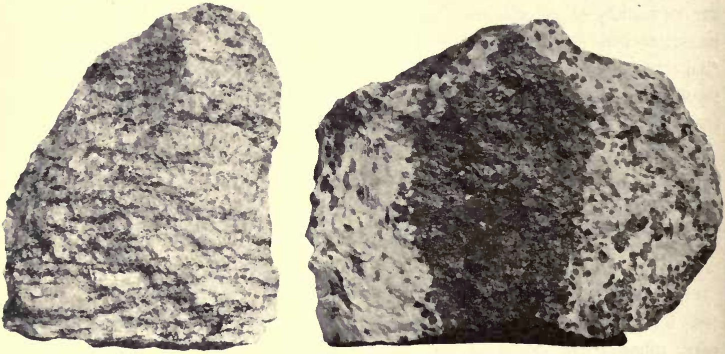

Fig. 14. Strings of garnet and dark inclusions (of clinopyroxene) with boundary-zones of garnet in the labradorite-rock from the Bergen-region.

In the specimen from Alvaerstrømmen there are frequent crystals of garnet in plagioclase (Ab_{65}), forming the main part of the rock. In the plagioclase also are enclosed rounded crystals of pyroxene and scapolite. A dark, sharply bounded veinlet, one centimeter in its thickest portion, intersects the rock in the manner of a dike. It is mainly composed of scapolite, enclosing rounded crystals of brownish violet augite and greenish brown hornblende, the latter almost opaque from pigmentary inclusions, and frequent euhedral crystals of apatite. The scapolite (wernerite) is gray from minute inclusions, 0.01 mm in maximum diameter, showing no polarizing effect and therefore being probably isotropic. Their refringence is high, and they may consist of some garnet mineral.

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[1] P. Eskola, On the Igneous Rocks of Sviatoy Noss in Transbaikalia. Öfversikt av Finska Vet.-Soc. Förh. XLIII, 1921, p. 66.

The occurrence of scapolite as a primary mineral in normal igneous rocks was described by me in some syenites from Sviatoy Noss, Transbaikalia[1]. Considering that the physicochemical conditions must, in solidifying magmas, be often nearly alike those at contactmetamorphic processes where scapolites originate, this mineral will probably prove to be rather common in different kinds of igneous rocks whose chemical composition is favourable for the formation of scapolite.

The Alteration of the Minerals in the Garnet-labradorite-rock.

The garnet and pyroxene, in the rocks of the Bergen region, show an alteration interestingly different from what was described from the eclogite of Nordfjord and Møre. Even with a rather superficial microscopic examination the alteration may be found to be connected with the saussuritization, often observed in the plagioclase.

Where the plagioclase has been saussuritized, there the garnet and pyroxene are always surrounded by altered zones, and I could verify an unmistakable correspondence between the degree of saussuritization and the breadth of the seams.

An advanced stage of this process was studied in a specimen marked "Manger field near Bergen". About a half of the rock-mass consists of a plagioclase, changed into a decimillimeter-grained mixture of granular albite ($\alpha' <$ n of the canada balsam $< \gamma'$) and prisms of zoisite. Crystals of clinopyroxene, a colourless variety, have been changed so far that only a central part, much less than a half of the original grain, has been left intact. In the garnet, on the other hand, alteration has made slow progress and only thin shells of the green minerals surround the large rounded crystals.

Between this advanced stage of change and the unaltered rock there are all degrees of gradual variation. I have studied a considerable number of thin sections of the labradorite-rocks from Mjeldem, Arnevaagen and S. of Tungeland near Bergen, the north part of Holsenø, Elsfjeld on Holsenø, and between Manger and Saebø. A photomicrograph (fig. 14, pl. III) shows a little advanced stage of the alteration.

At first sight the greenish zones around the garnets show some resemblance to the hornblende-kelyphite described earlier, and the zones around the pyroxene are sometimes not unlike the diopside-plagioclase symplectite, though their structure is more irregular. On closer examination, however, we find here quite other minerals, and the alteration of the garnet and of the pyroxene have led to almost the same products. — As Kolderup points out, the alteration zones contain, besides pale green hornblende, much chlorite, epidote and mica. The latter is in part colourless, a muscovite, but more generally a fainty pleochroic, pale green mica that might be taken for chlorite but for its strong birefringence. The same mica is also commonly met with in the saussurite-mass associated with zoisite. Amongst the alteration products I have, also, commonly observed margarite, known by its "micaceous" characters and $\gamma - \alpha$ about 0.010.

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[1] Op. cit.

In terms of the facies theory this kind of alteration means that the changes under consideration have proceeded in the greenschist facies and not in the amphibolite facies, as the alteration of the eclogites in Nordfjord and Møre. The rocks, after solidification, on their way towards the earth's surface, have happily surpassed the middle depth-zone, the amphibolite region, but still farther upwards been subject to differential movements and stress action promoting the change into, or nearly into, the greenschist facies.

Besides this greenschist-kelyphite there are also frequent examples of common amphibolite-kelyphite. In a specimen of garnet-labradorite-rock from the Kismul Mine all the pyroxene has been completely replaced, and the garnet in large part, by different zones of pure green hornblende. An incipient saussuritization has later left its impress on the plagioclase, but has not affected the hornblende.

Mineralogical Varieties of dark Segregations.

Concerning the dark segregations I have little to add to Kolderup's description. Three kinds were represented among the specimens studied by me: (1) Those of monoclinic pyroxene, with border-zones of garnet (specimens from Arnevaagen, near Bergen); (2) Segregations composed of green hornblende, with border-zones of garnet (Alvaerstrømmen); (3) Segregations composed of garnet, clinopyroxene and orthopyroxene without border-zones (specimens from several localities on Holsenø).

The last-named kind of segregations alone deserves description in this place, being one of the most interesting rocks studied by me. In one of the specimens, such segregations are of the size of the fist, but probably others of them are much larger. At all events, they, more than the other kinds of inclusions mentioned present the aspect of a true rock, and were that postulate omitted that an eclogite must contain clinopyroxene in the omphacite habit, this rock should be called hypersthene-eclogite. Here the clinopyroxene is a brown schillerizing variety showing most distinct diallage-parting and being filled up with pigmentary inclusions which in part make the mineral almost opaque. $c:\gamma = 45^\circ$. Axial dispersion is dictinct : $\rho > \upsilon$. This pyroxene makes up about two thirds of the rock-mass.

Next in abundance is the brownish red garnet, perfectly free from any inclusions.

The third main constituent is the hypersthene. Its colours are: α = brownish, β = reddish brown, γ = greenish grey. The optical character is negative and the axial angle about 75° or 80°. It should therefore contain some 25 of 30 per cent FeO.

The rock is free from feldspar, but there occur spots of saussuritized labradorite-rock which, under the microscope, give the impression of miarolitic cavities, crystal edges of all the minerals protruding from the surrounding. pyroxene-garnet-rock towards their centres. Towards these spots the clinopyroxene has developed thin zones of greenschist products, whilst, on the outer boundaries of the segregations, there are a little thicker zones of amphibolite products.

As minor constituents there are grains of iron ore with kernels of rutile. The latter is here, as in all rocks of eclogite character, decidedly the first formed mineral preceding the ilmenite which often accompanies it. The iron ore has sharp and clean boundaries towards the pyroxenes, but where it meets the feldspar, either in the miarolitic cavities or at the outer boundaries, there it is surrounded by a zone of posterior garnet in small grains, in part showing a myrmekite-like intergrowth with the feldspar. I have frequently seen this garnet in contact with the primary garnet, but it was not possible to decide the relation of their refringence. Apparently, however, they are different in composition, as they are in structure. A little reddish brown biotite has also grown around the ore-grains.

The structure of this rock is most interesting. The sequence of idiomorphism is distinct: diallage, garnet, hypersthene. This is the only rock in which I have seen xenomorphic garnet, in a striking manner filling up the interstices between the clinopyroxene-grains (fig. 15, table III). But where the garnet meets a crystal of hypersthene it assumes its usual rounded grain-shape and idiomorphic relation.

The great importance of this observation lies in the fact that we have a conclusive proof that the garnet is here a mineral that has crystallized directly from the magma. The idiomorphism of the garnets in our labradorite-rocks and eclogites, then, need not be regarded as the result of any greater energy of crystallization or other crystalloblastic properties, but simply to the prior separation, as in the other minerals in the igneous rocks.

Other inclusions consist of true eclogites. Among them some are well preserved in their original habit while others are greatly amphibolitized. Fig. 16 (pl. III) shows an example in which all the pyroxene has altered into a hornblende-plagioclase-mass with an ill-preserved symplectic structure.

The composition of the Garnet in the Labradorite-rock.

The analysis of garnet from labradorite-rock at Alvaerstrømmen given by Kolderup (see above p. 94) shows a mixture of nearly equal molecular quantities of magnesia and ferrous oxide, besides a low quantity of lime. The quantity of ferric oxide would seem to be exceptionally high, but the disagreement of the figures from the garnet formula makes it probable that this figure is too high. In other respects this garnet is exactly what we call an eclogite-garnet.

To learn more about the composition of these garnets I determined, with prisms, the index of refraction in three examples from the Bergen region. The results are given below with the resulting probable compositions. For comparison all that is known about the garnet in the labradorite-rocks from the Bergen and Sogn regions has also been quoted below.

	n_D	Probable Composition:
Garnet from labradorite-rock, Mjeldem	1.7506	$Fe_{29}Mg_{53}Ca_{18}$
—„— Arnevaagen	1.7542	$Fe_{32}Mg_{50}Ca_{18}$
Garnet from segregation, Saetre on Holsenø . .	1.7541	$Fe_{32}Mg_{50}Ca_{18}$
Garnet from labradorite-rock, Okken, Sogn . . .	1.7571	$Fe_{34}Mg_{48}Ca_{18}$
		Analyzed:
—„— Alvaerstrømmen . .	—	$Fe_{38}Mg_{40}Ca_{22}$
Garnet from segregation, Aurlandsfjord, Sogn . .	1.7658	$Fe_{38}Mg_{44}Ca_{18}$
Garnet from gabbro, Aardal, Sogn	1.7887	$Fe_{53}Mg_{33}Ca_{24}$

As appears, all the garnets from labradorite-rocks studied show a little more magnesia than iron, while the garnet from gabbro in Aardal shows iron predominating, being also in its occurrence more like common gabbro-garnets, which were invariably found to be almanditic.

The question now arises: is the presence of larger amounts of magnesia in the garnet from the labradorite-rocks than in the gabbro-garnets a consequence of larger concentration of magnesia in the rock, or is it due to specific physical conditions?

As will be shown latter, a somewhat high ratio of FeO is necessary for garnet in the gabbroic rocks. The labradorite-rocks are an exception to this rule. It will be useful, to compare what is known about the FeO:MgO ratios in garnets and the other mafic minerals in labradorite-rocks and gabbroic rocks. The following table will show these relations.

			FeO:MgO in hornblende etc.	FeO:MgO in garnets	
Gabbros and amphibolites	Suselbakke, Mysen	Hornblende	0.37	3.16	Garnet
	Taato, Kragerø	"	0.56	4.60	"
	Giving, Dybvaag	"	0.64	2.07	"
	Meinkjaer, Bamle	"	0.44	2.52	"
	Kantalahti	"	1.10	5.41	"
Labradorite-rocks	Aurlandsfjord, Sogn (Segregations)	Hornblende	0.37	0.86	Garnet
		Olivine	0.31		
		Hyphersthene	0.33		
		Anthophyllite	0.25		
	Alvaerstrommen, Bergen	Diallage	0.23	0.95	"
		Hornblende	0.31		
	Okken, Sogn	—	0.31	0.71	"

In all the rocks the garnet is the mineral by far richest in iron, but while the FeO : MgO quotients in the garnets from the labradorite-rocks are from 2.2 to 3.1 times higher than in the hornblende, they are from 3.4 to 8.5 times higher in the garnets of amphibolites and gabbros. Garnets comparable with those in the labradorite rock may only be found in the eclogites.

The clinopyroxenes in the labradorite rocks are, as we have seen above, highly aluminous, unlike the common diopsidic pyroxene, or "diallage", in gabbros and amphibolites and similar to the clinopyroxenes in the eclogites.

No further discussion is necessary in this place. The facts presented suffice to prove that the garnet in the labradorite-rocks and its segregations does not contain any such high proportion of iron as it does in the amphibolites and gabbros. As the difference is not due to the chemical composition, it must be a consequence of different physical conditions, and as the garnet in labradorite-rocks shares the wide range of mutual solid solutions of pyrope and almandite compounds only with the eclogite-garnets, we conclude that the former have originated under the same conditions, or in other words, the earliest segregations and crystallizations in the labradorite-rock belong to the eclogite facies; they are eclogites in process of formation.

Garnet-bearing Labradorite-rock in Other Regions.

It is, of course, of great interest to know, whether other occurrences of plagioclase-rocks, or anorthosites, share this feature of containing garnet of such eclogite-garnet character. Unfortunately I could not decide this with certainty. From the anorthosites and labradorite-rocks of Kiew and Wolynia in Russia[1] and Monhegan Island in Maine[2] no garnets have been mentioned. In the large Morin anorthosite mass[3] in Canada garnet is very common, but is often found near its contacts in varieties rich in iron ore. From its occurrence around iron ore grains where these are embedded in plagioclase it seems to be the usual posterior corona-garnet and is probably almandite.

Perhaps more similar to the Norwegian garnet-labradorite-rocks are the anorthosites of the Adirondacks[4] in which "deep pink garnets are well-nigh universal, and often associated in the most intimate way with the pyroxene. The relation makes one suspect that the garnet has resulted from preexisting pyroxene. In anorthosites proper reaction rims — do not appear".[5]

At any rate, these phenomena are exceedingly rare, and positive evidence of the existence of eclogite-like inclusions and eclogite-garnet has not yet been obtained from any area of labradorite-rocks other than those in the Bergen and Sogn regions in Norway.

Eclogite near the Sørdal Mine, Ytre Holmedal, Sogn og Fjordane Fylke.

Among all the occurrences of eclogite in the coast range only those at the Sørdal mine occur in immediate connection with Silurian rocks, here represented by mica-schists, quartzites and talc-schists, as described by Tellef Dahll[6]. The eclogite outcrops on the north side of a narrow valley, and on the other side, in contact with the schists, is found iron ore which contains lenses and bands of the eclogite garnet. The ore is a spinel-bearing magnetite-rock with 18.82 % TiO_2 and 51.33 % Fe.

This iron-ore is regarded by Tellef Dahll as a contact-separation from the eclogite, which he believes to be an igneous rock.

The eclogite has been described microscopically by Møhl, Riess and Kjerulf (see literature, p. 26). I have had thin sections made of specimens of this occurrence from Ramsgrønaave and Hørdens.

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[1] W. Tarassenko, abstract in N. J. 1899, I, 459.

[2] E. C. E. Lord, A. G. XXVI, p. 340, 1900.

[3] F. D. Adams, N. J. Min. etc. B.-B. VIII, 1893, p. 447.

[4] J. F. Kemp, Bull. Geol. Soc. Am. 1894, V, p. 216.

[5] Through the kindness of Dr. N. L. Bowen and Prof. W. J. Miller I was later able to determine the garnets in several specimens of anorthosite from the Adirondacks. They all proved highly almanditic (60 mol. % alm).

[6] M. Irgens og Th. Hiortdahl, Om de geologiske Forhold paa Kyststrækningen af Nordre Bergenhus Amt. Med. Tillæg 2: Jernforekomsten ved Sørdal af Tellef Dahll. Universitetsprogram for andet Halvaar 1864.

The specimens from Ramsgrønaave consist of garnet in ideal dodecahedra embedded in a medium-grained mass of light green clinopyroxene with pale green hornblende, brown rutile, quartz and apatite. The pyroxene shows $c : \gamma = 40^\circ$, and a positive axial angle larger than that in common diopsides. These properties conform with those found in the chloromelanitic pyroxene in the eclogite from Duen, Vanelvsdalen.

Certain bands in this eclogite contain numerous scales of light brownish yellow mica showing a small axial angle.

The perfect idiomorphism of the garnet is the most peculiar character of this eclogite.

The specimens from Hørdens, Hellevik, show a very peculiar structure. Visible to the unaided eye are ore crystalline aggregates in an aphanitic pale green mass. This mass consists almost exclusively of finely granular pyroxene, in which flakes of colourless mica occur in the manner of porphyroblasts. The crystalline aggregates consist of granular monoclinic pyroxene forming the central parts, surrounded by a granular mass of garnet, whose individual crystals show ideal dodecahedral forms towards the finely crystalline pyroxene mass forming the matrix. The minerals ot these eclogites show no sign of any alteration.

GARNET-AMPHIBOLITES AND GARNET-BEARING NORITES.

By studying the available analyses of garnets I had found the garnets in the garnet-amphibolites and gabbroid rocks always to contain almandite as the chief component. As such analyses were not very numerous, it seemed desirable to make some new investigations. Further, it could be presumed that garnet-bearing amphibolites had been eclogites before their metamorphism into the amphibolite facies. I therefore decided to determine whether there could be detected any relict features that would throw light on the question.

As the separation of the garnet in garnet-amphibolites is usually a difficult task, the mineral being generally stained with very minute inclusions of quartz and iron ore that in the aggregate frequently have the same weight effect as the garnet, I did not take the trouble of separating garnet in a pure form in more than one case, that of the garnet-amphibolite from Kantalahti. In other cases the mineral was used in the state of purity resulting after one separation with the Clerici solution. As the analyses thus have but a diagnostic value, to an approximate determination of their constituent isomorphous compounds, the determination of the state of oxidation was here omitted and all the iron was calculated as FeO.

Garnet-amphibolite from Kantalahti, Kola Peninsula.

In the southwestern part of the Kola Peninsula, around and west of Kantalahti bay, there occurs garnet-amphibolite on a very extensive area, forming a zone which probably continues hundreds of kilometers towards the Northwest[1]. This rock was first mentioned by A. Stelzner[2] and called an eclogite-like rock. Later on W. Ramsay gave a note of it[3]. To this same formation probably belong those rocks by E. v. Fedoroff described as drusites[4] and assumed to be a kind of igneous rocks.

A specimen of this rock, collected by professor W. Ramsay in 1890 and kept at the collection of the Mineralogical institute of the university of Helsingfors, was subjected to quantitative investigation by the writer. This rock was chosen in part because it seemed desirable to ascertain the composition of a rock type that has such an extensive occurrence, but more because I thought that this garnet-amphibolite might possibly be an amphibolitized eclogite.

The garnet in this rock, being filled up with minute inclusions of quartz, was very difficult to separate in pure form, and only after a threefold treatment with Clerici's solution alternating with crushing to a finer and finer grain was I finally successful in securing a practically clean material. I executed the analysis with the following result:

SiO_2	38.89	648	648
Al_2O_3	19.76	149	206
Cr_2O_3	0.00		
Fe_2O_3	1.95	12	
FeO	24.93	346	614
MnO	0.62	8	
MgO	2.54	64	
CaO	10.99	196	
TiO_2	0.73	9	
	100.41		

Sp. g. = 3.965 (t = 12°).

$n_D = 1.7889$.

$RO : R_2O_3 : SiO_2 = 2.98 : 1 : 3.15$.

Composition $(Fe_{57}Mn_1Mg_{10}Ca_{32})_3(Al_{94}Fe_6)_2$.

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[1] Cf. J. J. Sederholm's Geological Map of Fennoscandia in Bull. Comm. géol Finl. N:o 24, 1910.

[2] Bemerkungen über krystallinische Schiefergesteine aus Lappland. N. J. Min. 1886, II, p. 102.

[3] W. Ramsay, Fennia 15, IV, 1890.

[4] According to what several Russian geologists have told me. Fedoroff's original papers dealing with this subject have not been available to me.

The analysis of pure hornblende, made by the writer, gave the following result:

SiO_2	43.22	720
TiO_2	1.27	16
Al_2O_3	12.64	124
Cr_2O_3	0.00	—
Fe_2O_3	1.79	11
FeO	17.31	240
MnO	0.15	2
MgO	8.57	218
CaO	11.84	211
Na_2O	1.04	16
K_2O	1.21	13
H_2O	0.86	—
	99.90	

Sp.g. $= 3.27$ ($> 3.250 < 3.290$).

$\beta = 1.675 \pm 0.002$. $\gamma - \alpha = 0.016$ approximately, the negative acute axial angle $2V = 75^\circ$ appr. Axial dispersion not noticeable. $\beta = b$; $c : \gamma = 18^\circ$ appr. Pleochroism: α = yellowish green, β = dark olive green, γ = dark green. Absorption: $\alpha < \gamma < \beta$.

The mechanical analysis of the garnet-amphibolite gave the following result:

Iron ore	4.0 $^0/_0$
Titanite	3.0
Hornblende	39.4
Garnet	16.4
Biotite	6.0
Apatite	
Quartz	31.4
Plagioclase	
	100.2

The iron ore proved titaniferous, but a qualitative test made it probable that the ilmenite compound is rather subordinate. I assumed 1 $^0/_0$ ilmenite and 3 $^0/_0$ magnetite.

The titanite which is present as large elongated individuals of irregular shapes, was separated in a very pure form.

Biotite and apatite were not separated from one other; the amount ot the latter was estimated approximately at 1 $^0/_0$, that of the biotite thus being 5 $^0/_0$.

The colourless main constituents, quartz and plagioclase, sank on dilution of the liquid at the same time, having a nearly identical specific gravity. My efforts to estimate the relative amounts of these minerals by the Rosiwal method failed in consequence of the unequal distribution, the quartz occurring mainly as lenticular strings arranged parallel to the foliation, while the plagioclase, in the form of smaller grains, chiefly accompanies the hornblende. But so much is certain, that the amount of quartz is appreciably larger than that of the feldspar. The estimation of the quartz at 18 and the feldspar at 12.4 percent must be regarded as a crude approximation.

The feldspar shows, in sections ⊥ PM, extinction angles of about 10°. A faint inverse zonal structure may be seen occasionally. The average composition of the plagioclase should not be far from Ab$_{70}$.

For the dark brown biotite was assumed the composition of the lepidomelane from granite, Cape Ann, Mass. (Quant. Classif. table XIV, e).

Thus I arrived at the following mode:

Hornblende	39.4
Quartz	18.0
Garnet	16:4
Plagioclase (Ab$_{70}$)	13,4
Biotite	5.0
Titanite	3.0
Magnetite	3.0
Ilmenite	1.0
Apatite	1.0
	100.2

The specific gravity of the rock was directly determined at 3.146 (t = 12°). A calculation from the volumes of the minerals in the present mode gives sp. g. = 3.16, the close agreement being a check that the mode may be correct[1].

From these figures I calculated the following bulk composition of this rock:

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[1] Errors in the mutual proportions of quartz and feldspar would, however, not influence the calculated sp. g. as both minerals are identical in their specific gravities.

	0/0	Mol. numb.	Mol. 0/0	Norm	
SiO_2	52.1	868	55.3	Quartz................	11.16
Al_2O_3	12.1	119	12.3	Orthoclase.............	5.56
Cr_2O_3	0.0	—		Albite.................	13.62
Fe_2O_3	3.5	22		Anorthite..............	23.07
FeO	13.8	192	14.6	Σ sal	53.41
MnO	0.2	1			
MgO	3.8	95	5.9	Diopside..............	15.41
CaO	8.8	157	9.7	Hypersthene...........	20.50
Na_2O	1.6	26	1.6	Magnetite.............	5.10
K_2O	0.9	10	0.6	Ilmenite...............	4.56
TiO_2	2.4	30		Apatite...............	1.00
P_2O_5	0.4	3		Σ fem	46.20
H_2O	0.5				
	100.1		100.0		99.61

Sp. gr. = 3.146 (t = 12°).

III, 4, 4, 3, Koghose.

In the present case it would be useful to have a direct bulk analysis of the rock to check this calculation whose premises are not quite accurate. Meanwhile, however, we may use the figures arrived at and we will find some peculiar features that can be stated with full confidence. Such is the great preponderance of ferrous oxide over magnesia, appearing in both the chief mafic constituents. Another peculiar characteristic of this rock is the comparatively high percentage of silica combined with a low proportion of alumina, appearing mineralogically in the large quantities of quartz, in a rock whose other main constituents are hornblende and almandite. The arrangement of the quartz in the form of elongated stringers would perhaps suggest the idea that silica might have been added during some metamorphic processes whereby the bulk composition would have undergone considerable changes from an original composition more normal gabbroic.

The following considerations, however, do not seem to be in favour of such an hypothesis. For the first, doubtless primary volcanic and abyssal rocks sharing this chemical character are not by any means rare, and there are, in Washington's tables, closely similar analyses of koghoses. For the second, it is known that, in a northwesterly direction from the Kantalahti district, almandite-bearing granitic rocks, so-called granulites or leptynites, underlie immense areas in Finnish Lapland and Norwegian Finnmark. These facts suggest a genetic connection between these granulites and the Kantalahti rocks, and the suggestion seems to be supported by a striking chemical relationship apparent from available analyses of the granulites[1]. We may only quote the analysis (I) by Naima Sahlbom of a granulite-gneiss from Finnish Lapland, composed of quartz, potash and soda feldspar, biotite, rutile and garnet, beside the figures for our garnet-amphibolite (II):

	I	II
SiO_2	73.98	52.1
Al_2O_3	14.93	12.1
Fe_2O_3	0.26	3.5
FeO	9.34	13.8
MnO	0.00	0.2
MgO	0.36	3.8
CaO	1.92	8.8
Na_2O	3.14	1.6
K_2O	5.07	0.9
TiO_2	tr.	2.4
P_2O_5	0.00	0.4
H_2O	0.11	0.5
	100.11	100.1

This analysis of granulite-gneiss as well as the other analyses of related rocks published by Hackman show all a very high proportion of silica combined with a high percentage of iron in preponderance over magnesia, just as the Kantalahti rock. It seems therefore most probable that we have to do with a petrographic province whose comagmatic rocks are characterized by the chemical features just named.

Before returning to the question whether the garnet-amphibolite of Kantalahti may have originally been an eclogite we shall at first look at its structural characters, illustrated by the microphotograph, pl. III, fig. 17. Rounded grains of garnet, 8—10 mm in diameter, stained with minute quartz-grains, are embedded in a foliated mass in which anhedral grains of hornblende in poikiloblastic intergrowth with rounded enclosed small feldspar grains form elongated lenticular groups in which also the grains of the biotite, titanite and iron ore are concentrated. The granular quartz forms similar groups, and the parallel arrangement of all these give the rock a pronounced foliation. It is a typical structure of a crystalline schist.

The rock could therefore very well, at some earlier stage, have been an eclogite in which the pyroxene was latter converted into feldspar and hornblende, the rutile into titanite, and the garnet alone been preserved as a relic. A feature in the composition of the garnet would even support this supposition: its lime content which is higher than that met with in the average garnets of the amphibolites. But this is not sufficient evidence, and there is none more positive. Thus this question must be left unanswered.

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[1] Victor Hackman, Die chemische Beschaffenheit von Eruptivgesteinen Finnlands und der Halbinsel Kola. Bull. Comm. géol. Finl. N:o 15, 1905, analyses 84—87.

One thing is certain: The existence of the garnet in this amphibolitic rock depends upon the iron-prevalence in the rock, a feature common in all the garnet-amphibolites investigated by me.

Garnet-amphibolite from Suselbakke, Mysen, Smaalenene, Norway.

The specimens of garnet-amphibolite from Suselbakke in the parish of Mysen, Smaalenene, have been derived from the Archaean of Southern Norway. It is labeled "amphibolite in granite-schist", from which it appears that it may have been a mixed rock where lenses of amphibolite are included in granites. With the naked eye can be discerned a decimillimeter-grained ground-mass with visible black prisms of hornblende and grains of feldspar. In this mass are embedded grains of red garnet, from one to two millimeters in diameter. From the rock the garnet was separated by a single treatment with Clerici's solution and analyzed by the writer with the following result:

	%	Mol. numb.
SiO_2	40.82	680
TiO_2	0.79	10
Al_2O_3	19.40	190
FeO	25.04	342
MnO	1.13	15
MgO	4.49	112
CaO	8.48	152
	100.15	

Sp. g. = 3.94.

n_D = 1.7852.

$RO : R_2O_3 : SiO_2 = 3.26 : 1 : 3.58$

(TiO_2 has not been accounted for, as it certainly has been derived from inclusions of ilmenite.)

Composition $Fe_{55}Mn_2Mg_{18}Ca_{25}$.

The sample contained some ilmenite and quartz. The figure for Fe is therefore too high, but there is no doubt that iron is largely preponderant in this garnet.

The granular ground-mass is mainly composed of brown hornblende and labradorite, besides smaller amounts of titanite and iron ore.

The amphibole has a very feeble pleochroism for a hornblende, and the colours are brown in all directions, but faintly greenish brown on γ. The strongest absorption belongs to β. The negative acute axial angle is not far from 90°. The other characters are those of normal common hornblende. $\beta = 1.655 \pm 0.003$, corresponding to 10 % FeO and 15 % MgO.

The plagioclase has a noticeable inverse zonal structure. I observed a section ⊥ PM where the extinction angle on the border was + 35° and in the centre but 30°. On the whole the plagioclase should contain a little less than 50 per cent albite.

Garnet-amphibolite from Taatø near Kragerø.

The specimen investigated was collected by Professor W. C. Brøgger in 1902. According to information kindly furnished by Professor J. Schetelig such rocks commonly occur as schliers or long bands in the granite area of Bamle. They have some resemblance to the amphibolitic border zones of the norite and hyperite-masses in the same tract, but they show no apparent connection with them.

It is a millimeter-grained hornblende-plagioclase-rock containing abundant crystals of garnet, up to 2 cm in diameter. Associated with the garnet and almost of the same size are lumps of quartz. Scales of biotite may be discerned with the unaided eye in the ground-mass.

An analysis of the garnet made by the writer resulted in the following figures:

	%	Mol. numbers
SiO_2	39.17	653
Al_2O_3	18.61	182
FeO	29.08	404
MnO	1.63	23
MgO	3.75	94
CaO	5.47	98
TiO_2	2.03	
	99.74	

Sp. g. = 4.00

n_D = 1.7970.

$RO : R_2O_3 : SiO_2 = 3.40 : 1 : 3.72$.

Composition $Fe_{65}Mn_4Mg_{15}Ca_{16}$.

The sample contained much quartz and iron ore (ilmenite). Hence the deviation from the garnet ratio.

It may be seen, under the microscope, that the ore grains are evenly distributed and enclosed in all the minerals including garnet.

The hornblende is of the common green variety, having $\beta = 1.665 \pm 0.003$. The plagioclase shows, in sections ⊥ PM, extinction angles of $25^\circ - 27^\circ$, corresponding to $Ab_{53} - Ab_{50}$.

Minor constituents are apatite and zircon.

Sometimes the hornblende and sometimes the plagioclase shows greater tendency towards an idiomorphic development, and it is not possible to state with certainty, whether the structure may be regarded as crystalloblastic or as a consolidation structure.

The refringence of the hornblende ($\beta = 1.665$) points, according to Ford's diagrams, to a hornblende containing about 13 percent FeO and 13 percent MgO, or an amphibole with a considerable molecular preponderance of magnesia. This is interesting, the garnet being so very much richer in the iron compound.

Hornblende-gabbro from Haugen, Meinkjær, Bamle.

The specimen studied was collected by W. Werenskiold and represents the amphibolitic border zone of a norite mass. It is a medium-grained feldspar-hornblende-rock containing red crystals of garnet of the size of peas at rather regular intervals of two or three cm.

The garnet was separated and an analysis of it was made by the writer with the following result:

	%	Mol. number
SiO_2	38.65	644
Al_2O_3	20.89	205
FeO	28.57	397
MnO	0.78	11
MgO	6.48	162
CaO	4.34	78
TiO_2	0.57	8
	100.28	

Sp. g. = 3.984.

$n_D = 1.7864$.

$RO : R_2O_3 : SiO_2 = 3.11 : 1 : 3.14$.

Composition: $Fe_{61}Mn_2Mg_{25}Ca_{12}$.

The garnet is poor in inclusions. Only grains of ilmenite were observed in it and these are as numerous, when enclosed in the garnet, and of the same shape as when enclosed in the other minerals.

The sample was therefore very pure and the deviation from the garnet ratio is probably solely due to the non-determination of ferric iron.

Plagioclase is somewhat more abundant than the hornblende and shows, in sections $\perp$ PM, extinction angles of 24°, corresponding to the composition Ab_{55}.

The hornblende is brownish green, of the common character, with comparatively faint pleochroism and large axial angle. $\beta = 1.660 \pm 0.003$, corresponding to about 11 per cent FeO and 14 MgO.

Apatite is abundant, and occasionally there occur flakes of biotite penetrating all the other minerals.

This rock has clearly a primary consolidation structure, appearing especially in the fact that the plagioclase is idiomorphic in its relation to the hornblende.

As to the conditions of the existence of garnet in this rock we refer to what will be said below, in the discussion of the garnet-bearing norite.

Garnet-Amphibolite from Arøen, Kragerø.

The garnet-amphibolite from Arøen, Kragerø, is a medium-grained hornblende-plagioclase-rock containing frequent large crystals of red garnet, almost filled up with inclusions of quartz. This garnet showed

$$n_D = 1.7917$$

corresponding to the composition $Fe_{59}Mg_{37}Ca_{24}$. Even if the proportion of lime differs from this calculated value, the main character of this garnet is at any rate the same as in all the other amphibolite-garnets, with preponderating almandite-compound.

Norite from the vicinity of Tvedestrand.

The specimen investigated was derived from an erratic boulder found in Giving, Dybvåg. It is a medium-grained rock where the feldspar grains are tabular on M (ophitic structure) and arranged parallel to one another. Some pyrrhotite is visible to the unaided eye, and sparingly garnet. Of the latter mineral there was, in the specimen, but one large crystal (2 cm in diameter) and a few smaller. These crystals are almost free from inclusions, so that the sample for analysis prepared from the large crystal, was practically clean. The result of my analysis is the following:

	%	Mol. number
SiO_2	39.45	657
Al_2O_3	23.04	225
FeO	24.73	344
MnO	1.34	18
MgO	6.88	172
CaO	4.94	88
TiO_2	0.21	3
	100.59	

Sp.g. = 4.02.

n_D = 1.7823.

$RO : R_2O_3 : SiO_2 = 2.76 : 1 : 2.93$.

Composition: $Fe_{55}Mn_3Mg_{28}Ca_{14}$.

Concerning the other minerals the following may be noted:

About a half of the rock-mass consists of plagioclase, showing, on P, extinction angles of 12°, corresponding to a labradorite.

Another colourless mineral is scapolite of the wernerite series, especially frequent in the vicinity of the garnet crystals, but also found with the other mafic minerals.

Among the latter, brown hornblende is the most abundant, occurring in groups of fine grains and associated with scaly iron ore. The hornblende has $\beta = 1.670 \pm 0.003$, corresponding, according to Ford's diagram, to 14 % FeO and 12 % MgO. The mineral shows a strong pleochroism and other usual characters.

A little brown biotite accompanies the hornblende and is also found as coronas around crystals of ilmenite in the usual manner.

The hypersthene is also arranged in groups of fine grains. These show a faint greenish (γ) and reddish (α and β) pleochroism and an axial angle about $\alpha = 70°$ approximately, corresponding to about 40 mol. % $FeSiO_3$.

The groups of hypersthene are surrounded by coronas, or reaction rims, essentially composed of green hornblende. This hornblende has a little lower mean index of refraction than the brown one ($\beta = 1.670$). It is speckled with minute rounded, isotropic grains of dark green colour, apparently spinel.

Some of these reaction zones are still surrounded by another zone of garnet, this mineral thus appearing in two generations.

Adding the apatite, the list of constituents should be complete so far as the primary igneous and the posterior minerals of the amphibolite facies are concerned. There are also some hydrated products of decomposition.

The boulder from which this specimen was taken has probably been transported by the land-ice from some of the numerous elongated norite masses in the neighbourhood of Tvedestrand and further north in Bamle, known especially because they, at many points, are the mother-rocks of nickel-bearing pyrrhotite[1]. Such a locality, in close vicinity of Dybvåg, is Høiås near Tvedestrand.

A. Lacroix[2] gave a microscopic-petrographic description of gabbros from Ødegården in Bamle and Høiås (by Lacroix written Heias). He paid much attention to the coronas, and found zones of garnet in different kinds of such coronites. From the Høiås mine he described a corona around hypersthene, consisting of green hornblende with spinel, quite as that observed by me. Lacroix also observed cases where the central kernel consists of olivine surrounded by double zones of hypersthene and hornblende (op. cit. p. 234). The granular character of the hypersthene in my slice suggests the idea that the hypersthene would here also be a synantetic mineral having completely replaced the olivine.

Among the two generations of garnet that one occurring as large crystals no doubt crystallized directly from the magma. At first sight, one could believe that the garnet might belong to quite an early stage of rock development, an eclogitic stage. But really it is not so. The distribution of the garnet-bearing varieties as boundary-zones in the rock-masses, a fact with which at first professsor J. Schetelig kindly made me acquainted, gives some evidence on this point.

The relations have been described by J. H. L. Vogt[3] from the nickel-ore fields of Ertelien in Ringerike, Dyrhaug in Værdalen etc. On a minute scale the phenomenon, in pyrrhotite-bearing norite, is a typical corona, appearing only at the contact against plagioclase. But it may happen that there is, at the boundary between the sulphide and the norite a compact zone of garnet from 5 to 10 mm in thickness passing gradually over into the normal norite.

The formation of garnet is favoured by a high proportion of iron, as apparently the almandites have a wider field of existence than those mixtures containing appreciable amounts of magnesia. Now the iron in proportion to the magnesia, in a crystallizing magma-mass, is presumably highest at the contact against a segregated mass of iron sulphides. Therefore garnet has been formed there.

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[1] J. H. L. Vogt, Bildung von Erzlagerstätten durch Differentiations-Processe in basischen Eruptivmagmata, II. Zeitschr. f. praktische Geologie, 1893, p. 125. Older litteratur has been quoted there (p. 131).

[2] A. Lacroix, Contribution á l'étude des gneiss à pyroxène et des roches a wernérite. Bull. soc. fr. de minéralogie, XII, 1889.

[3] Op. cit. p. 140.

There is, however, still another condition favouring the formation of garnet. This mineral, as a constituent of the coronas, belongs to the stage of hornblende-gabbro facies. Now, many of the norite and gabbro masses in Southern Norway pass, towards their borders, gradually over into hornblende-gabbro or amphibolite. To put it in the terms of the facies-principle, the boundary zones of these masses have crystallized under conditions not far from those of the hornblende-gabbro facies. These boundary zones often contain almandite, a mineral not appearing in the typical gabbro facies, although its field of stability exceeds the upper temperature limit of the pure hornblende-gabbro facies. Therefore we may speak about an intermediate facies, at a certain very limited range of variation in the composition characterized by the occurrence of almandite.

This example, just as the other examples of garnet-bearing gabbros and amphibolites of whose garnets analyses are available (cf. Mineral Facies, p. 171), show invariably garnets with prevalent almandite. In this respect they differ from the eclogites, and other rocks genetically connected with eclogites (cf. p. 101), whose garnets vary within a wide range between those extremely high in almandite to those containing as much as 75 per cent pyrope.

Explanation of the plates.

All the photomicrographs were taken with unpolarized light. Magnif. 14 diam.

Pl. I.

Fig. 1. Eclogite from olivine-rock. Almklovdalen. Garnet and clinopyroxene.

Fig. 2. Chloromelanite-eclogite of the Duen type. Vanelvsdalen. Garnet with zonal structure (not visible in the reproduction) and chloromelanite. The dark boundary lines consist of diopside-plagioclase-symplectite.

Fig. 3. Olivine-eclogite, Lyngenes, Sørpoll, Selje. Garnet, clinopyroxene and olivine.

Fig. 4. Eclogite, Silden, Selje. Garnet, clinopyroxene, quartz and a little biotite and rutile.

Fig. 5. Eclogite-hornblendegabbro, Romsdalshorn. Garnet (a large crystal in the lower half), plagioclase (light), pyroxene (gray grains in the upper half, in part intergrown with the plagioclase), biotite (a large individual), hornblende (with the garnet) and black iron ore.

Fig. 6. Enstatite-eclogite, Sætre on Hareid. The clinopyroxene is greatly altered into diopside-plagioclase-symplectite (dark boundaries). The light grains with almost black boundary-zones are enstatite.

Pl. II.

Fig. 7. Eclogite, Gurskø. Alteration into diopside-plagioclase-symplectite (appears dark) n the clinopyroxene works inwards with sinuous boundaries.

Fig. 8. Eclogite, Leinekiven, Bøland. Greater part of the clinopyroxene has altered into diopside-plagioclase-symplectite.

Fig. 9. Eclogite, Sætre on Hareid. Greater part of the clinopyroxene has altered into diopside-plagioclase-symplectite. Garnet as elongated grains with kelyphite shells, remains of clinopyroxene, and enstatite (with black alteration zone, lower left hand side).

Fig. 10. Eclogite, biotite-bearing. Coarse-structured diopside-plagioclase-symplectite, and zones of hornblende-kelyphite round the garnet. Hegerskjæret, Hustadviken.

Fig. 11. Garnet-amphibolite, formed by alteration of eclogite. All the pyroxene in the earlier diopside-plagioclase-symplectite has been uralitized. Thick zones of hornblende-kelyphite are seen around the residual garnet. Silden, Selje.

Fig. 12. Kelyphite-amphibolite, from eclogite. Only small remains of garnet have been left. The rutile has altered into ilmenite. Silden, Selje.

Pl. III.

Fig. 13. Eclogite-hornblendegabbro, Brandsæter, Kornstadfjord. The interstices of the idiomorphic garnets are filled up with a granular mass of hornblende and plagioclase.

Fig. 14. Garnet and clinopyroxene in saussuritized labradorite-rock. Both minerals are surrounded by zones of hydrated minerals. Mjeldem near Arnevaag, Bergen.

Fig. 15. "Hypersthene-eclogite" with xenomorphic garnet (light). The largest pyroxene-grains are clinopyroxene. Holsenø.

Fig. 16. Amphibolite-eclogite, Arne, Bergen.

Fig. 17. Garnet-amphibolite, Kantalahti, Kola. Composed of garnet (with inclusions of quartz), hornblende, biotite, quartz, titanite and iron-ore.

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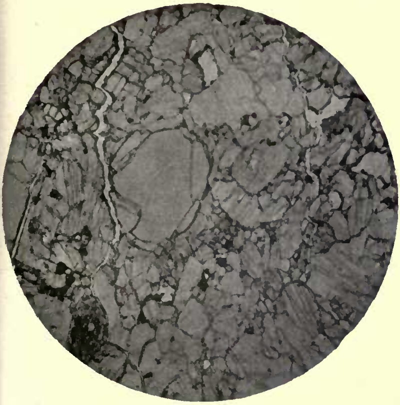

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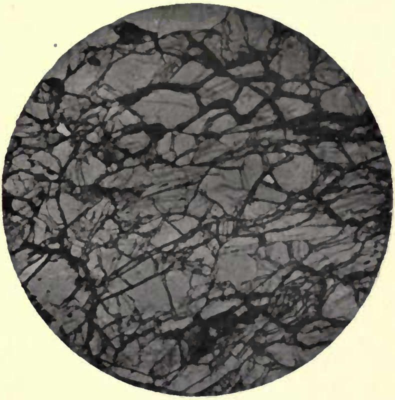

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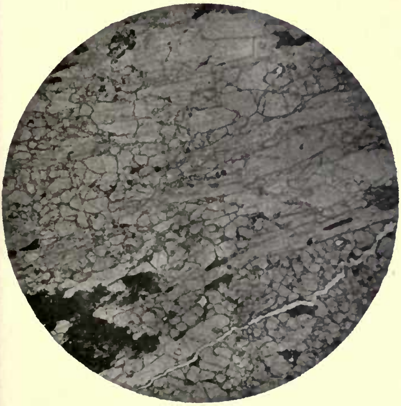

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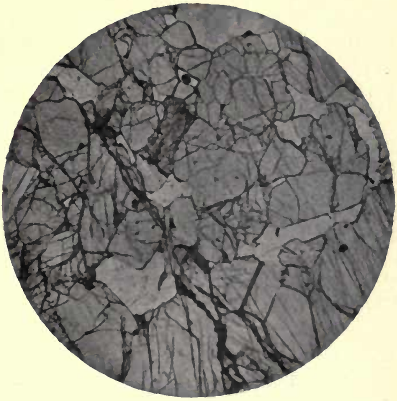

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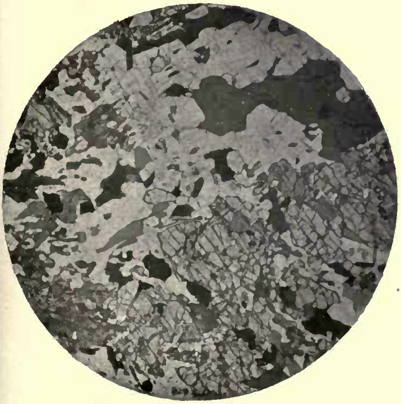

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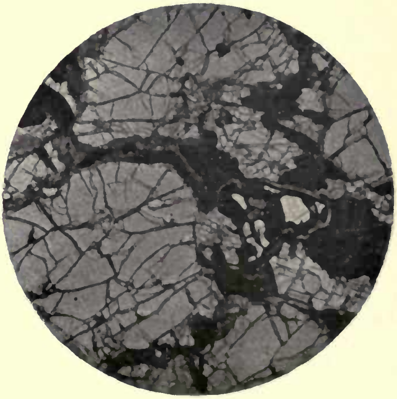

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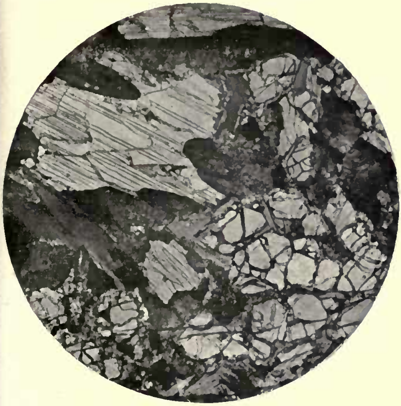

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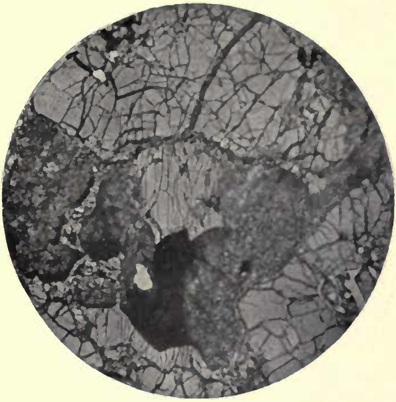

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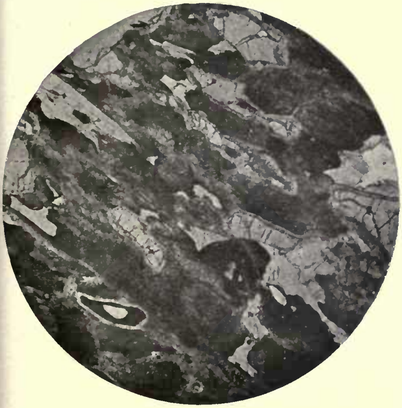

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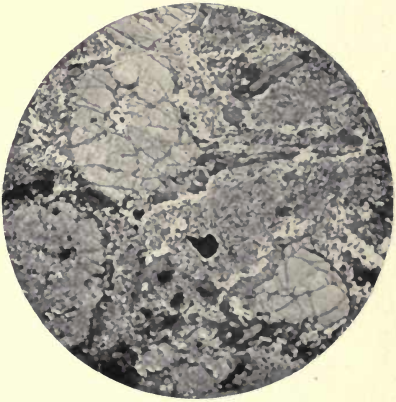

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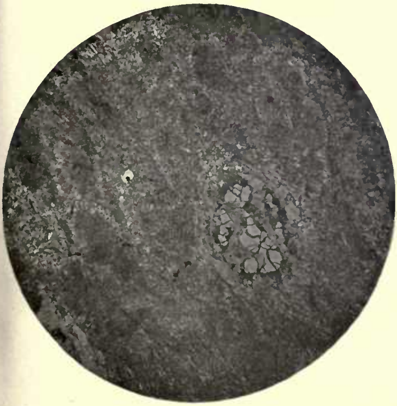

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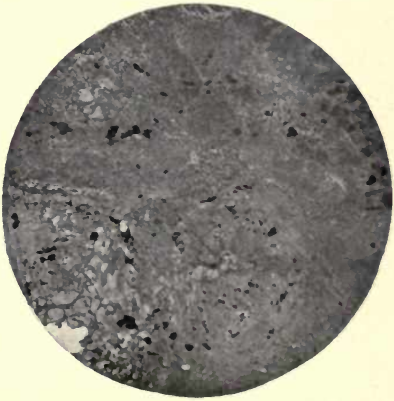

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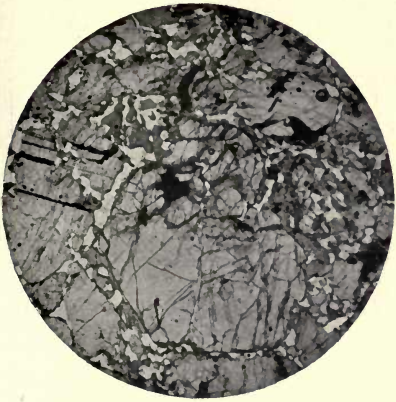

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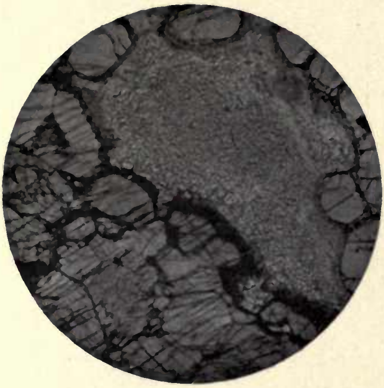

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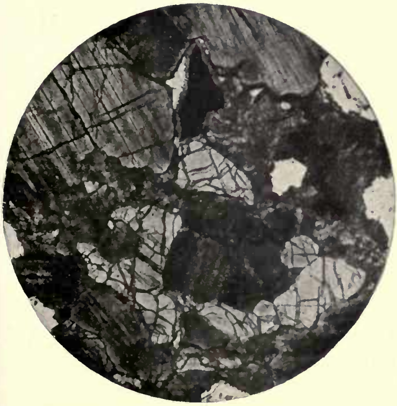

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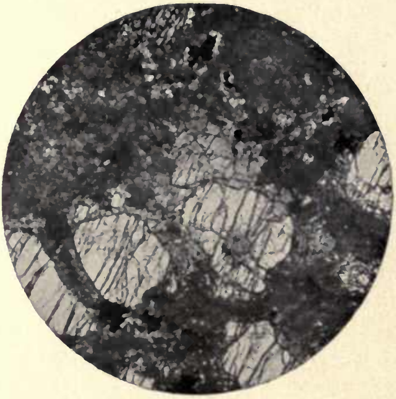

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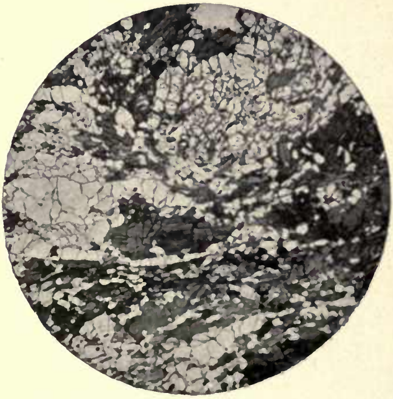

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